2021-03-15

Offshore longline mussel farms: a review of oceanographic and ecological interactions to inform future research needs, policy and management

Mascorda Cabre, Llucia

http://hdl.handle.net/10026.1/16967

University of Plymouth

REVIEWS IN Aquaculture

Reviews in Aquaculture, 1–24 doi: 10.1111/raq.12549

Offshore longline mussel farms: a review of oceanographic and ecological interactions to inform future research needs, policy and management

Llucia Mascorda Cabre, Phil Hosegood, Martin J. Attrill, Danielle Bridger and Emma V. Sheehan

School of Biological and Marine Sciences, Faculty of Science and Engineering, University of Plymouth, Plymouth, UK

Correspondence
Llucia Mascorda Cabre, University of Plymouth Marine Institute, 3rd Floor Marine Building, Drake Circus, Plymouth PL4 8AA, UK.
Email: llucia.mascordacabre@plymouth.ac.uk

Received 19 October 2020; accepted 7 February 2021.

Abstract

With a growing human population and the need to protect our oceans from overfishing, there is a requirement for society to source alternative means of sustainable protein. Mussel aquaculture has rapidly expanded in many countries serving as an important supply of protein, but its development has been limited due to competition for coastal space and the associated environmental impacts of farming in inshore waters. Offshore aquaculture developments have the potential to overcome such issues. This review synthesises the current literature on the ecological and oceanographic interactions of longline offshore mussel farms with the aim to elucidate the main knowledge gaps in a context of management and conservation. Large offshore aquaculture installations interact with the hydrodynamics of the area causing water flow distortions and current attenuation, wake formation and distorting water column stratification which can have an effect on the supply of nutrient and seston as well as altering material dispersal, biodeposition and resuspension, having in turn, a knock-on effect on the carrying capacity of the system, ultimately affecting the surrounding ecology and its ecosystem services. Offshore mussel farm studies report an increase biomass or numbers of benthic and pelagic organisms beneath and around mussel ropes relative to control sites using the structure for shelter, refuge and nursery. Improving our understanding of offshore aquaculture–environment interactions is crucial to identify the priorities needed for future research to inform policy and management practices as well as its role as part of the Blue Growth Agenda and as 'other effective area-based conservation measures' (OECMs).

Key words: aquaculture, blue growth, ecology, marine protected areas, mussel farm, oceanography.

Introduction

The 21st century is faced with the challenge of satisfying human demand for sustainable protein (Duarte *et al.* 2009; Strand *et al.* 2017). World fish consumption has increased from an average of 9.9 kg per capita in the 1960s to 20.3 kg per capita in 2016, with 151.2 million tonnes in total produced for human consumption (FAO 2018). Capture fisheries have not been able to keep up with this increase in demand (Jackson *et al.* 2001; Pauly *et al.* 2002; Galparsoro *et al.* 2020) as over 89% of global wild marine fish stocks are overexploited (FAO 2016), with production remaining relatively static since the 1980s. Such shortfall has been met by increasing marine farming of finfish, shellfish and seaweed (Duarte *et al.* 2009; Strand *et al.* 2017; Landmann *et al.* 2019).

Over the past 50 years, global aquaculture has grown and expanded dramatically, accounting for almost half of the world's fish food supply from marine sources and reaching 110.2 million tonnes in 2016 worth an estimated value of USD 243.5 billion (FAO 2018). It is one of the fastest growing production industries on the planet with a current annual growth rate of 5.8% since 2001, with China being at the forefront holding 61.5% of the world's production (FAO 2018). Such growth has been related to the 'Green Revolution' (greater grain yields since 1950s) being named a 'Blue Revolution' (O'Donncha *et al.* 2016). This requires increasing use of public coastal space putting the industry's development into conflict with other users and societal demands such as tourism, nature protection, fisheries, energy production or transport (Stelzenmüller *et al*. 2013; Callier *et al*. 2017; Strand *et al*. 2017; Lacoste *et al*. 2018; Lester *et al*. 2018; Landmann *et al*. 2019; Galparsoro *et al*. 2020).

This paper aims to review the interactions that offshore longline mussel aquaculture farms have in relation to the offshore physical and ecological marine environment by explaining our current understanding of (i) the effect of farms on background oceanography; (ii) the consequent ecological effects and response; (iii) the relevance in a context of management, policy and conservation; and (iv) the main knowledge gaps that need addressing in order to foster the development of a sustainable industry.

Bivalve aquaculture

The latest FAO State of the World Fisheries and Aquaculture 2018 report states that the global shellfish industry produced 17.1 million tonnes of molluscs (USD 29.2 billion) in 2016, representing 58.8% of the combined production of marine and coastal aquaculture. Mussels accounted for about 8% of shellfish production with around 15 million tonnes. China is the largest producer of aquaculture mussel (14.2 million tonnes) accounting for 83% of total production (FAO 2018).

As one of the most important non-fed species in aquaculture (no need to be provided with an external source of food as filter feeding organisms directly feed on the plankton in the surrounding environment; Lucas 2012; FAO 2016; STECF 2018), molluscs are the most consumed aquaculture category after finfish (Table 1; Ellis *et al*. 2007; FAO 2018; STECF 2018). With the appropriate environmental conditions, molluscs such as mussels and oysters that have a free-swimming larval stage will also self-seed providing a relatively cost–effective harvestable crop if suitable habitat is provided (Stevens *et al*. 2008). Naturally, mussels and oysters are ecosystem engineers that form large wild beds. These biogenic reefs provide important services through their effects on nutrient cycling, habitat structure, water filtration, biodiversity and food web dynamics. Due to their appeal as a food source, exploitation of natural beds for commercial purposes (dredging) and farming is widespread (Tyler-Walters 2008; Strand *et al*. 2017; Landmann *et al*. 2019).

Types of mussel farming

Mussels can be produced by either 'bottom' or 'off-bottom' cultivation accounting for approximately 15% and 85% of overall production, respectively (Mckindsey *et al*. 2011). Bottom culture involves dredging mussels from natural subtidal or intertidal beds to move them to more sheltered areas where they can expand and grow. To help reduce the heavy predation by crabs and starfish attracted to bottom culture, the vast majority of cultivated mussels are grown 'off-bottom', suspended above the seabed (Spencer 2002).

Table 1 Farmed organisms harvested from global aquaculture for human consumption in 2016

Category	Number of species	Production (tonnes)	Value (USD 1000)
Finfish	369	54 091 148	138 537 549
Molluscs	109	17 139 140	29 201 729
Crustaceans	64	7 862 016	57 078 984
Others†	16	938 558	6 766 010
Total	558	80 030 862	231 584 272

†Frogs, reptiles and aquatic invertebrates. *Source*: Modified from FAO (2018b).

There are three principle methods of off-bottom culture: raft, pole and longline (STECF 2018). In raft culture (Fig. 1a), seed is attached to ropes suspended from moored, floating rafts (Aypa 1990). Pole culture (Fig. 1b), or 'bouchot', involves growing mussels on wooden stakes driven into the ground in low intertidal zones (Mckindsey *et al*. 2011; Goulletquer 2020). The most employed technique is the continuous longline design (Fig. 1c,d) as it supports a substantial crop with minimum infrastructure (Stevens *et al*. 2008; STECF 2018).

Although it is a rapidly evolving industry, longline farms are typically large developments of at least 100 ha with more than 200 longlines. With an average length of 120–150 m, each longline consists of two parallel 'backbone' ropes supported by buoys at regular intervals keeping the structure afloat and moorings anchored to the seabed (Fig. 1c,d; Plew 2005; Plew *et al*. 2005; Stevens *et al*. 2008). Mussels are attached to line droppers, evenly spaced ropes that continuously loop from the 'backbone' and have lengths between 5 and 30 m depending on water depth and nutrient availability (Stevens *et al*. 2008; Landmann *et al*. 2019). In areas with strong currents, waves and winds, longline farms have been submerged 5–10 m using buoyancy controls or altering the mooring design (Fig. 1d) allowing mussels to grow faster and have higher meat/shell ratios, making them a preferred method and becoming the dominant technique used (Buck 2007; Stevens *et al*. 2008; Brenner *et al*. 2009; Kapetsky *et al*. 2013; Gagnon & Bergeron 2017).

Impacts of inshore mussel farming

Overall, aquaculture systems have two main outputs of pollution: animal faeces and waste from added feed which accumulate under and around the structures as biodeposits

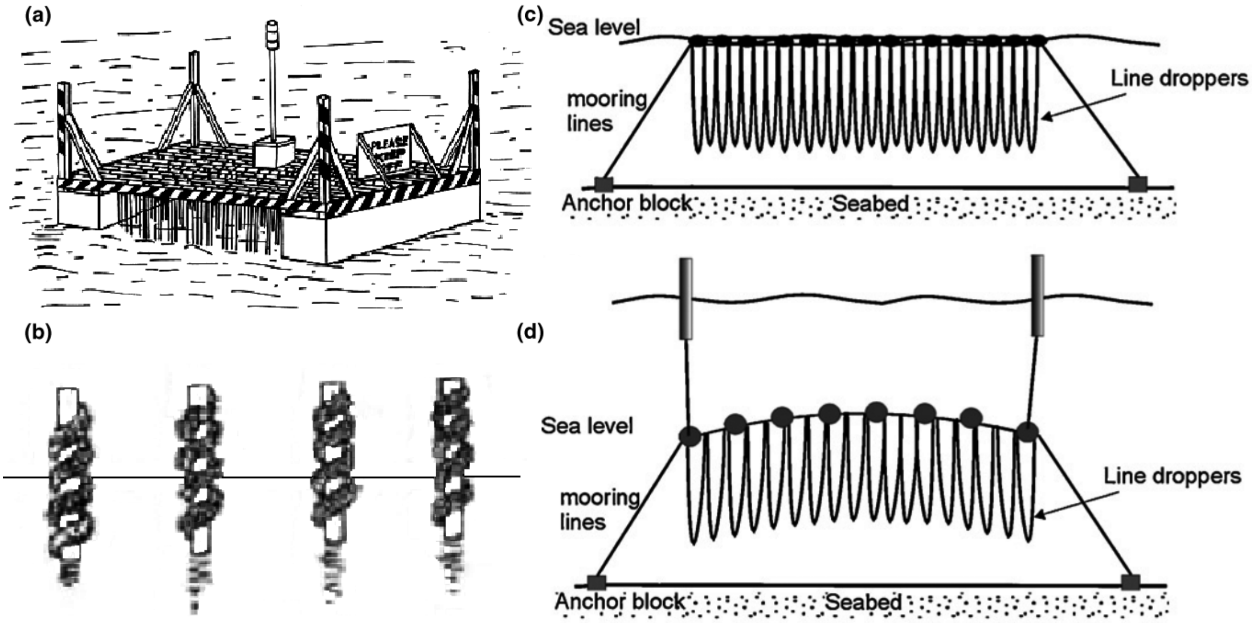

Figure 1 Types of mussel farm design: (a) raft (Aypa 1990), (b) pole or 'bouchot' (Goulletquer 2020), (c) longline and (d) submerged longline (Stevens *et al.*2008).

(Giles *et al.* 2009; Keeley *et al.* 2009; Rampazzo *et al.* 2013; Hilborn *et al.* 2018). Inshore mussel farms located in low energy environments with a mild hydrodynamic regime are considered to have localised effects (Chamberlain *et al.* 2001; Hartstein & Stevens 2005; Callier *et al.* 2006; Giles *et al.* 2009). Non-fed aquaculture such as bivalve farming does not report to have as many negative effects as finfish farming (Danovaro *et al.* 2004; Fabi *et al.* 2009; Keeley *et al.* 2009; Rampazzo *et al.* 2013; Hilborn *et al.* 2018).

With a role in the provision of ecosystem goods and services, mussel farms can mitigate the consequences of nutrient loading and eutrophication (Ferreira *et al.* 2011; Kumar & Cripps 2012; Gallardi 2014; Matarazzo Suplicy 2018; Newell *et al.* 2019) having a positive contribution to the surrounding ecology due to their sediment stabilisation capacity, biofiltration function and ability to uptake CO_2 (Matarazzo Suplicy 2018; Sheehan *et al.* 2019; Solandt *et al.* 2020). Research indicates that production of non-fed species can be a more sustainable source of protein crucial in providing food security with minimal environmental impact (FAO 2016; Hilborn *et al.* 2018; Matarazzo Suplicy 2018). This has been acknowledged worldwide by environmental groups and certification bodies, such as World Wildlife Foundation (WWF) and Aquaculture Stewardship Council (ASC), as being a highly sustainable form of seafood production (Matarazzo Suplicy 2018) and are recommended as a 'best choice' or 'super green option' by the Marine Conservation Society (Marine Conservation Society 2018).

Nonetheless, with the intensification of shellfish farming in sheltered inshore locations, the increased amounts of biodeposits in the form of faeces, pseudofaeces and marine litter are accumulated beneath and around the farm, affecting the benthic community structure below (Chamberlain *et al.* 2001; Hartstein & Stevens 2005; Callier *et al.* 2006; Fabi *et al.* 2009; Keeley *et al.* 2009; Mckindsey *et al.* 2011; Kumar & Cripps 2012; Rampazzo *et al.* 2013). This is amplified by changes in water flow velocities as the farm obstructs any background currents present showing that local hydrodynamic regimes have a major influence on a farm's magnitude and severity of effects, especially in low energy environments (Grant & Bacher 2001; Strohmeier *et al.* 2005, 2008; Cranford *et al.* 2009; Stevens & Petersen 2011; Matarazzo Suplicy 2018). The large amounts of organic loading can influence biogeochemical processes, altering sediment physicochemical parameters that have an effect on benthic respiration with wider ecological effects including the creation of novel habitat and ultimately the modification of benthic infaunal communities. As organic matter (OM) increases, natural soft-sediment communities dominated by large filter feeders are replaced by smaller, opportunistic deposit-feeding organisms and altering pelagic assemblages (Chamberlain *et al.* 2001; Danovaro *et al.* 2004; Newell 2004; Hartstein & Stevens 2005; Callier *et al.* 2009; Fabi *et al.* 2009; Keeley *et al.* 2009; Grant *et al.* 2012; Rampazzo *et al.* 2013; Matarazzo Suplicy 2018). Raising concerns about the increasing range of aquaculture–environment interactions of intensive bivalve aquaculture

(Kumar & Cripps 2012; Gallardi 2014; Landmann *et al.* 2019) have led the industry to acquire a certain negative reputation within the public view (Gentry *et al.* 2017).

Inshore mussel farms have been found to increase the structural complexity of the seabed underneath due to mussel fall-off from the ropes, creating habitats for other invertebrates by providing food and refuge from predation (Gutiérrez *et al.* 2003; Sheehan *et al.* 2019) and attracting scavengers and other predators (Inglis & Gust 2003; D'Amours *et al.* 2008). Studies have reported diverse assemblages of fish, invertebrates and algae as well as an increase in biodiversity and biomass (LeBlanc *et al.* 2003; Murray *et al.* 2007; Sheehan *et al.* 2019). Other effects include the aggregation of epibenthic macrofauna and the modification of plankton communities (Chamberlain *et al.* 2001; Mckindsey *et al.* 2011; Bendell 2014; Gallardi 2014).

Generally, mussel farms have varying effects on the marine benthic environment and associated benthic assemblages depending on the type of culture and the oceanography and hydrodynamic regime of the area (Chamberlain *et al.* 2001; Mckindsey *et al.* 2011; Kumar & Cripps 2012); while some report negative impacts (Kaspar *et al.* 1985; Stenton-Dozey *et al.* 1999, 2001; Chamberlain *et al.* 2001; Nizzoli *et al.* 2005, 2006; Hargrave *et al.* 2008; Cranford *et al.* 2009; Keeley 2013) others result in little or no ecological change relative to surrounding habitats (Crawford *et al.* 2003; Inglis & Gust 2003; Danovaro *et al.* 2004; Lasiak *et al.* 2006; D'Amours *et al.* 2008; Ysebaert *et al.* 2009; McKindsey *et al.* 2012; Wilding & Nickell 2013; Dimitriou *et al.* 2015).

A move from inshore to offshore mussel farming

As the inshore industry is reaching a saturation stage with its expansion becoming a potential space usage conflict, offshore shellfish developments are becoming increasingly attractive by extending the industry to high hydrodynamic areas, reducing spatial constraints, visual effects, increasing production capacity and potentially reducing the ecological effects experienced by inshore developments (Gibbs 2004; Plew *et al.* 2005; Stevens *et al.* 2007, 2008; Brenner *et al.* 2009; Keeley *et al.* 2009; Kapetsky *et al.* 2013; Gallardi 2014; Fairbanks 2016; Gentry *et al.* 2016, 2017; O'Donncha *et al.* 2016; Gagnon & Bergeron 2017; Buck *et al.* 2018; Lacoste *et al.* 2018; Landmann *et al.* 2019; Muñiz *et al.* 2019). Compared to inshore environments which tend to be oligotrophic in nature, offshore environments have good water quality with continuous good oxygen conditions, lower nutrients and lower primary productivity reducing the risks of exposure to biotoxins such as toxic phytoplankton blooms (red tides), and low exposure to diseases, parasites or terrestrial sources of contamination such as pollutants and pesticides, common issues of inshore mussel farming (Buck *et al.* 2005; Stevens *et al.* 2007, 2008; Brenner *et al.* 2009; Lucas 2012; Kapetsky *et al.* 2013). Therefore, offshore mussel farms may not only increase production but have the potential to grow healthier and qualitatively better mussels than those grown inshore, compensating the investment (Brenner *et al.* 2009).

Following the need for a more precise definition suitable for the development of a common legal framework as required by the United Nations Convention on the Law of the Sea (UNCLOS), this paper defines 'offshore aquaculture' as:

> the establishment of aquaculture farms in exposed locations, in areas with a high energy environment and exposed to substantial oceanic conditions (large waves, storms and strong currents) located more than 1 km from the nearest coast and requiring reasonable infrastructure

This definition is, therefore, encompassing other terms such as 'remote area', 'open water', 'open ocean', 'offshore' or 'off-coast', used in the literature to define the type of farm under review, but focusing on the physical and environmental conditions of the area (Ryan, 2004; Plew *et al.* 2005; Stevens *et al.* 2008; Troell *et al.* 2009; Kapetsky *et al.* 2013; Lovatelli *et al.* 2013; Froehlich *et al.* 2017b; Buck *et al.* 2018).

As oppose to what is seen inshore, offshore mussel farms are situated in highly dynamic systems with high energy background currents and waves capable of dispersing biodeposits (Fabi *et al.* 2009; Kumar & Cripps 2012; Lin *et al.* 2016; Lacoste *et al.* 2018). Although the significant volumes of organic loading produced by mussel farms have the potential to be dissipated, offsetting the effects seen beneath inshore developments (Lin *et al.* 2016; Lacoste *et al.* 2018), the structure itself may have an effect on water flow (Plew *et al.* 2005, 2006; Tseung *et al.* 2016). The influence of small farms to an area with a high energy hydrodynamic regime is likely to be small compared to the natural variability and dynamics of an offshore marine environment. However, the effect of large developments like that of a typical offshore longline mussel farm may be substantial causing blockage to the flow and dissipating energy (Plew *et al.* 2005, 2006; Tseung *et al.* 2016). High hydrodynamic regimes can alter the rate at which biodeposits accumulate and/or dissipate extending the footprint of an offshore mussel farm over larger areas (Giles *et al.* 2009; Lacoste *et al.* 2018), indicating a strong relationship between the oceanography of a farm, organic enrichment in seabed sediments and a subsequent modification of macro-invertebrate and pelagic composition (Fig. 2; Fabi *et al.* 2009; Rampazzo *et al.* 2013; Lin *et al.* 2016; Lacoste *et al.* 2018).

Despite the potential benefits of offshore farming, there is very limited offshore aquaculture presence due to economic costs, suitability of location in terms of hydrodynamic regime and ecological carrying capacity, the need for planning and large-scale infrastructure engineering designs (Stevens *et al.* 2008; Buck *et al.* 2018; Lacoste *et al.* 2018; Galparsoro *et al.* 2020), licensing intricacies and lack of clear policy and management, social perceptions and political obstacles (Kapetsky *et al.* 2013; Upton & Buck 2010; Fairbanks 2016; Galparsoro *et al.* 2020). Additionally, the limited knowledge describing the influence of offshore developments available is causing difficulties for this industry to flourish. Particularly, quantitative and qualitative relationships between farming level and benthic influences are lacking, making predicting environmental farm effects challenging (Mckindsey *et al.* 2011; Upton & Buck 2010; Froehlich *et al.* 2017a).

In order for this industry to develop and become a sustainable source of protein, it is paramount that we understand its potential impacts to assess and quantify its benefits and be able to optimise its development and management. Expansion of the offshore aquaculture industry requires improved understanding of aquaculture-ecologic and oceanographic interactions (Fabi *et al.* 2009; Stelzenmüller *et al.* 2013; Upton & Buck 2010; Lin *et al.* 2016; Tseung *et al.* 2016; Callier *et al.* 2017; Strand *et al.* 2017; Lacoste *et al.* 2018; Lester *et al.* 2018; Landmann *et al.* 2019; Galparsoro *et al.* 2020), crucial to clarify what needs to be prioritised to inform consenting, useful impact assessments, efficient marine spatial planning (MSP) and inform policy makers within a context of ecosystem-based management.

Methods

Following an extensive amount of research and literature on the effects of inshore mussel farms, this review concentrates its literature review on a critical account of what has been published on offshore longline mussel farms. Specifically, the areas relevant to its influence on water flow and consequent ecological effects were identified as the main focus for a thorough literature review analysis through keyword searches in scientific journals, 'grey' literature and press publications.

A basic background information check was performed in order to establish the need for this review and to identify the most relevant literature available. Then, a general literature search through Google Scholar and Web of Science

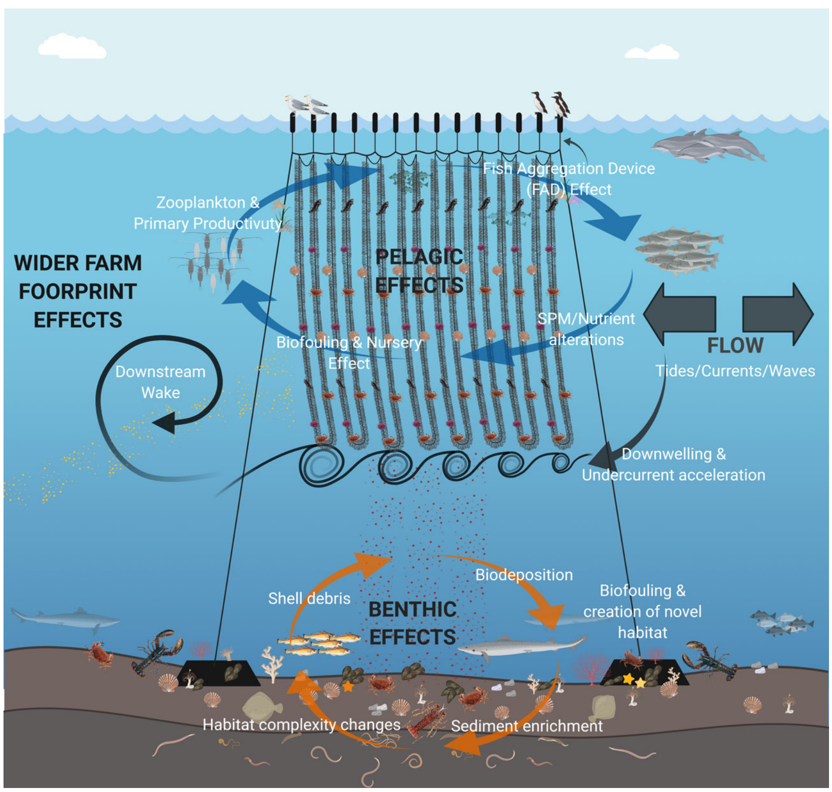

Figure 2 Main potential ecological and oceanographic effects of a longline mussel farm. The figure represents one many designs that could be attributed to offshore longline mussel farm's constantly evolving outlines (Graphic Mascorda Cabre 2020 created with BioRender.com).

was used to have an overview of the topic which included search terms such as 'offshore shellfish', 'offshore aquaculture', 'remote aquaculture', 'open water aquaculture', 'open ocean aquaculture', 'off-coast aquaculture' and any combination of those as well as searching for relevant literature reviews already published. This was followed by a more specific literature research which expanded on previous terms to include keywords such as 'mussel', 'longline', 'long-line', '*Mytilus*', '*Perna*', 'oceanography', 'flow', 'hydrodynamic', 'current regime', 'management', 'conservation', 'ecology', 'plankton', 'MPA' and any combination of those in Google Scholar, Web of Science, Elsevier and ScienceDirect on publications between 2000 and 2020.

A paper management system (Mendeley®) was used to store and classify the relevant literature which was filtered by date. Literature was then read and assessed on its relevance to this review. Where literature directly assessed the effect of offshore mussel aquaculture on benthic and pelagic ecosystems or oceanographic and ecological effects, the papers were identified as key references for each topic and used accordingly. When a Google search identified literature in English, French or Spanish, these were analysed however, literature was specifically searched in English only. Any other language not spoken by the authors was omitted from the analysis.

While there likely exists other publications that look at offshore aquaculture, such as 'polyculture' or 'renewable energy', these studies were not included since the focus of this review was to assess the specific knowledge in regard to offshore longline mussel farms alone.

Results

This section describes the results of a thorough literature review on the knowledge regarding the effects of offshore longline mussel farms to date.

Influence of offshore farms on water flow

Large offshore aquaculture installations impact local hydrodynamics by acting as physical obstacles to water flow. As a porous structure, water flow blockage is partial, differing from the effects that other well-studied solid structures (i.e. islands or sea defences) have on the flow (Plew *et al.* 2006; O'Donncha *et al.* 2013) by creating velocity shears and mixing layers and producing small-scale turbulence causing enhanced dispersion (Fig. 3; Plew *et al.* 2005, 2006; O'Donncha *et al.* 2013, 2016; Plew 2013; Matarazzo Suplicy 2018). For instance, reducing current velocities within the farm (drag-induced modifications) resulting in an effect on the velocity profile of the water column, generating increased vorticity and vertical circulations at the flanks with the acceleration of currents beneath it (Plew *et al.* 2005, 2006; Shi *et al.* 2011; Tseung *et al.* 2016) which may have considerable impacts to the surrounding environment which could result in an increase seabed scour and biodeposit resuspension (Danovaro *et al.* 2004; Plew *et al.* 2005, 2006; Fabi *et al.* 2009; Plew 2013; Rampazzo *et al.* 2013; Tseung *et al.* 2016). Due to increased drag, it may also determine the formation of a wake downstream of the farm (Figs 2,3; Plew *et al.* 2005, 2006; Tseung *et al.* 2016).

Although environmental impacts of shellfish aquaculture focus on ecological aspects such as biodeposition, nutrient depletion and benthic impacts, extensive effects may be associated with wave attenuation, wake formation, current distortion and disruption of stratification (Boyd & Heasman 1998; Grant & Bacher 2001; Plew *et al.* 2005, 2006; Strohmeier *et al.* 2005; Stevens *et al.* 2008; Plew 2013) which will in turn inform the extent of a mussel farm's ecological impacts and footprint. Perturbations in the current regime may have an effect on the supply of nutrient, seston, material dispersal and feeding behaviour, if not taken into account, this could result in an overestimate of the overall carrying capacity of the system and should not be neglected (Duarte *et al.* 2008; O'Donncha *et al.* 2013; Plew 2013; Lin *et al.* 2016). Such effects are closely related to the underlying hydrodynamics of the area. Particularly, its carrying capacity or performance will be influenced by a range of factors such as the overall dimensions, extent, shape and layout of the farm (orientation of the farm's structures to prevailing currents and waves and/or spacing between headlines), the density of both the farm and the mussels on the ropes (farm's canopy), the bathymetry, topography and geology of the area, the current and weather regime characteristics (background current speeds) as well as the ecology, physicochemical and biological parameters of the surrounding marine environment (Aure *et al.* 2007; Stenton-Dozey 2013; Lin *et al.* 2016; Pechlivanidis *et al.* 2018).

A collection of elements that form a porous obstacle to water flow can be described as canopies. For instance, terrestrial forests, wetland marshes and kelp beds are naturally occurring canopies which have been broadly studied showing to reduce water flow velocities within, generate velocity shears, mixing layers and producing small-scale turbulence which enhance dispersion (Jackson & Winant 1983; Plew *et al.* 2005, 2006; Rosman *et al.* 2013; Hondolero & Edwards 2017). Contrary to emergent canopies that extend upwards from the floor and, when aquatic, are either fully or partly covering the entire water column, mussel farms are highly porous structures that extend downward from the water surface and present a gap between the canopy and the seabed or bottom boundary thus referred to as suspended canopies (Plew *et al.* 2006; Tseung *et al.* 2016). When a suspended canopy extends downwards few metres

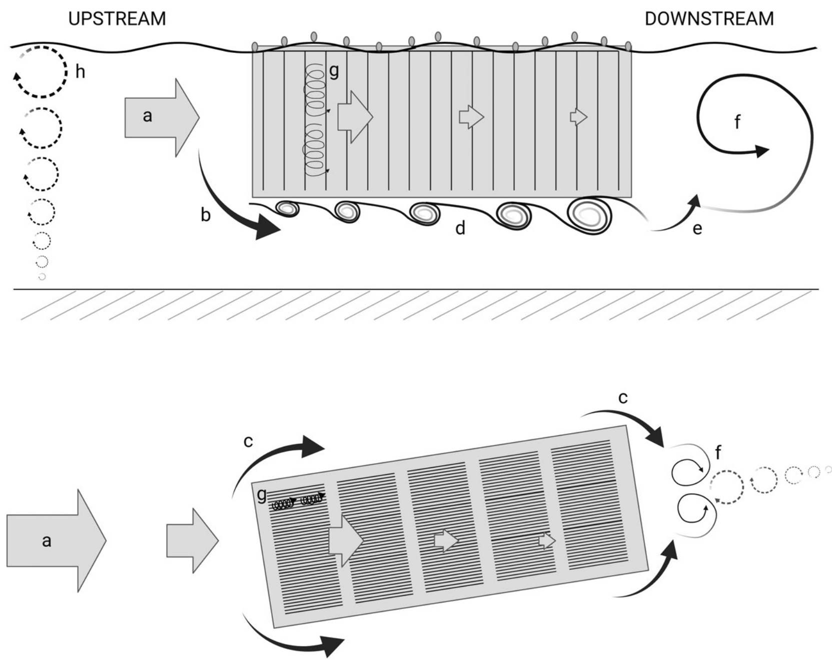

Figure 3 Elevation (top) and plan views (bottom) of an offshore longline mussel farm indicating various potential hydrodynamic processes: (a) water flow and current attenuation, (b) downwelling, (c) corner acceleration, (d) accelerating undercurrent mixing layer, (e) upwelling, (f) recirculating zone, vortex or wake formation downstream of the farm, (g) turbulence within mussel longlines and (h) waves. The figure exemplifies one of many designs that could be attributed to offshore longline mussel farm's constantly evolving outlines (Graphic Mascorda Cabre 2020 created with BioRender.com, adapted from Plew *et al*. 2005).

below the water surface, this can also be referred to as submerged canopy such as those created by submerged longline mussel farms (Plew *et al*. 2006).

In order to understand water flow interactions of shellfish suspended canopies, the extensive relevant literature around emergent canopies is indebted, especially in terms of flow distortion and current attenuation, edge effects, patchiness, within canopy transport, wake formation and interaction with stratification. However, it must be noted that unlike natural canopies, shellfish structures are highly ordered and heterogeneous canopies in terms of organisation (longline spacing, depth, dropper diameter…) (Stevens & Petersen 2011).

Water flow modification

In coastal areas, emergent canopies rooted to the seafloor such as seagrass meadows, salt marshes, mangroves and kelp forests provide shore protection by preventing erosion, increasing sedimentation and mitigating flooding by restraining waves and currents due to their wave attenuation capacity. Although the ecosystem services of such emergent canopies are relatively well studied, aquatic suspended canopies which have most of their biomass near the surface such as certain forests of kelp (*Macrocytis* sp), vegetated platforms that serve as breakwaters or longline mussel farms which may provide similar ecosystem services have been neglected (Plew *et al*. 2005, 2006; Mckindsey *et al*. 2011; Alleway *et al*. 2019; Chen *et al*. 2019).

During wave attenuation, energy is transferred from the wave field to turbulence as the waves propagate through a canopy. Although wave-driven flexible structures such as a longline mussel farms move and flex to accommodate this transfer of energy, such drag-induced water flow velocity modifications have been detected within suspended aquaculture structures (Plew *et al*. 2005) where bottom friction and structure drag generated turbulence within the canopy has shown the potential to enhance mixing both horizontally and vertically (Fig. 3; Plew *et al*. 2006; Stevens *et al*. 2008). As longline mussel farms do not extend over the full water depth, flow diversion is expected to be both vertically and horizontally around the canopy being the latter the predominant direction as longline mussel farm dimensions are two to three orders of magnitude greater horizontally than vertically (Plew *et al*. 2006). This is supported by hydrodynamic studies of offshore mussel farms showing that water flow velocities are reduced both near the bed (bottom boundary layer friction) and within the canopy, while the highest velocities are found around and beneath the farm, in the gap between the seabed and the bottom of the suspended canopy (Fig. 3; Plew *et al*. 2006; Plew 2013).

Limited field studies show that some of the water flow approaching the farm is diverted under and around inducing downwelling on the upstream side of the farm (Plew *et al.* 2005; Rampazzo *et al.* 2013; Lin *et al.* 2016). The spatial distribution of such flow changes is not simple as there are areas for instance, around the corners of a farm and beneath, where the disturbed flow accelerates (Stevens *et al.* 2008). Currents within the suspended canopy have been found to be as little as 25% those of the outside water flow with water speed reductions reaching up to 90% in extreme cases (Plew 2013; Lin *et al.* 2016; Hulot *et al.* 2018). A study of an inshore but highly hydrodynamic mussel farm in Cobscook Bay (USA) used hydrodynamic and material transport models to show how flow is diverted around the farm with velocities increasing outside the structure while flow attenuation is up to 50% at the centre (O'Donncha *et al.* 2016).

Studies have identified that a main factor key to water flow modification is the angle of inference between upstream longlines and water flow. If upstream longlines are aligned to the flow, only a fraction of water goes through which is substantially slowed down creating great velocity gradients (Delaux *et al.* 2011) although, this could reduce seston supply as downstream ropes would be within the influence of upstream ones (Plew 2005). Alternatively, when perpendicular to the current, water flow modification is widely spread creating less vorticity (Delaux *et al.* 2011). Both small (0°C; Delaux *et al.* 2011) and large (90°C) angles have been found to cause greater drag and greater alterations to vertical flow (Plew *et al.* 2006; Delaux *et al.* 2011). This can be attenuated by lower space between ropes (Plew 2005); hence, drag is a function of farm orientation to the flow, density, spacing and ultimately, overall farm arrangement (Plew 2005; Stevens *et al.* 2008; Delaux *et al.* 2011; Smaal *et al.* 2019). Taking into account the angle of the farm to the flow and water residence time (the time a particle spends in a given place, how long it takes to go through the system) within the canopy Plew *et al.* (2006) found that farms perform best when developed approximately 45°C to the flow while, Delaux *et al.* (2011) found that larger farms at 50–90°C angle to the current, water flow reduction was decreased.

Water flow velocity increases beneath the farm may both affect the location of biodeposit material on the seabed and increase seabed shear stress increasing the possibility of sediment and biodeposit resuspension influencing the depositional footprint of the farm (Giles *et al.* 2009; Plew 2013; Rampazzo *et al.* 2013). The increase in flow velocity beneath the farm strongly depends on the farm's density stratification and the gap between the bottom of the farm and the seabed. Numerical models suggest that highest beneath the farm velocities occur when longlines extend to about 80% of the water depth (Plew ,2011, 2013). A study of New Zealand mussel longline farms has shown that beneath the farm velocities are offset by around the farm horizontal water flow diversion producing an increase in seabed shear stress of up to 20% (Plew ,2011, 2013).

Another implication of flow modification by longline mussel farms is the influence of depth and near seabed water flow. Although there's an overall lack of information about velocity changes with depth in large suspended canopies, increased velocities on the seabed of a mussel farm have been measured (Plew 2005). When developed in deeper water, it is more likely that a greater water diversion under the canopy occurs (Plew *et al.* 2006); however, in shallower waters for instance where the gap between the canopy and seabed is around 0.1 and 0.3 of the water depth, the underflow appears to be restricted. Although a smaller gap increases below farm water velocity, this in turn increases velocities within the farm and bed friction which restricts such underflow (depth-average velocity) reducing vertical transport. This effect is greater as the gap decreases (Plew *et al.* 2006; Plew 2011). This is further demonstrated by numerical models where the size of the gap beneath the farm shows to modify bed shear stress up to a 66% increase (assuming no water diversion around the farm) which could increase sediment transport and resuspension (Plew 2011). In an actual farm, water flow is diverted horizontally as well as vertically resulting in a reduction in depth-average velocity which has been estimated to be of about 40% (Plew 2011). It has been suggested that increasing canopy density lowers velocities within the canopy relative to higher below the canopy velocities, generating greater bed friction and total drag (Plew 2011) while increasing canopy thickness may alter longline drag due to its proximity to the seabed (Plew 2005).

Wake formation

A region of flow recirculation behind an object, a wake, can be formed downstream of a mussel farm (Plew *et al.* 2005, 2006; Tseung *et al.* 2016). The wake consists of two main zones, a steady wake with approximately constant velocity and a velocity recovery zone where velocity increases again (Tseung *et al.* 2016; Figs 2,3). As upstream longlines divert the water flow producing lower velocities within the farm and acceleration around and/or beneath it (Gibbs *et al.* 1991; Plew *et al.* 2006), numerical and experimental studies indicate the possible balanced of such flow alterations by the formation of a steady slow velocity wake downstream, where longlines have lower drag, with a subsequent velocity recovery zone (Tseung *et al.* 2016).

Stratification distortion and particle residence time

Through a study of an offshore mussel farm in New Zealand, Plew *et al.* (2006) suggested that lower dissipation rates downstream of the farm could be due to a low-velocity wake formation while orientation of longlines to the water flow have an important influence on the farm's net drag and wake formation (Plew *et al.* 2005; Delaux *et al.* 2011). Numerical models suggest that flow distortions can reach considerable distances (from 0.6 to 4 times the canopy length) from the structure (Tseung *et al.* 2016), observing different degrees of water flow acceleration away from the installations depending on background hydrodynamics and farm structure.

The effects of offshore longline aquaculture farms on material transport and residence times are important in terms of carrying capacity and the extent of a farm's footprint (Stevens *et al.* 2008; Plew 2013). The pulse residence time (PRT) is the time needed to flush a given fraction (95%) of a conservative tracer or dye from a water body after being introduced to a given location. PRT can be seen as a self-purification capacity measure of a farm thanks to both tidal exchange rates with the outer sea and turbulent dispersion. Even in an inshore development under high current velocities, flushing times can be increased as high as 10–20% within its footprint (O'Donncha *et al.* 2016), reducing food renewal flows and accumulating biodeposits within the structure by altering sedimentation rates (Stevens *et al.* 2007, 2008; Lin *et al.* 2016; O'Donncha *et al.* 2016) which can then be transported further afield by beneath farm accelerating currents. Therefore, changes in current speeds, even when localised, can impact material transport altering the farm's footprint.

Differences in water density due to temperature and salinity cause stratification (layering of water bodies) which can reduce PRT, limiting both nutrient and biodeposit flux in and from the canopy. Longline mussel farms may influence these by blocking or diverting water layers, generating internal waves or enhancing vertical mixing through within farm turbulence (Plew 2013). Changes in the depth and layout of isopycnals have already been observed in the field due to offshore mussel farm structures interacting with stratification (Plew *et al.* 2005, 2006; Plew 2013). Experimental studies have shown that stratified water moving through a porous structure can produce internal waves which can be propagated away from the structure (Plew 2013) and that density stratification can inhibit vertical diversion favouring horizontal diversion instead (Plew *et al.* 2006) or even restrict the development of the shear layer and further reduce vertical diversion and transport (Plew 2011). However, the influence of stratification depends on a wide range of factors such as background hydrodynamics or tides as well as the surface and density of the farm. This can also have an effect on the formation and extend of a wake (Plew 2013). Such interactions are poorly understood and its magnitude and spatial scales are key to determine any ecological consequences hence more research is needed (Stevens *et al.* 2008; Plew 2013).

Ecological interactions with offshore farms

The influence of offshore large structures on the surrounding environment and the current regimes of the area can influence various ecosystem processes which can result in a range of direct and cascading effects on the surrounding ecosystem (Fig. 2). For instance, by adding physical structure to the environment both through the introduction of hard infrastructure, which contributes to ocean sprawl (Heery *et al.* 2017) and the organisms themselves, which in turn can modify hydro-sedimentary processes as they modify currents, increase local sedimentation and biodeposits (Kumar & Cripps 2012; Landmann *et al.* 2019) or create new habitats for benthic assemblages (Mckindsey *et al.* 2011; Sheehan *et al.* 2019).

Benthic ecology and habitat modification

Biodeposition and benthic enrichment. As filter feeders, mussels pump water in and trap suspended material. Undigested and unwanted material is mixed with mucus and expelled as faeces and pseudofaeces, respectively (Chamberlain 2002; Spencer 2002; Mckindsey *et al.* 2011). The magnitude of these depend on the quality and quantity of food available with a greater fraction of pseudofaeces being produced when seston quantity is high and/or seston quality is low (Mckindsey *et al.* 2011). It is estimated that mussels assimilate 80% of ingested food (Chamberlain 2002).

Mussel farm biodeposition material varies greatly in size as it also includes mussel shell (Hartstein & Stevens 2005). Biodeposits sink at greater velocities than their constituent particles, increasing the flux of OM reaching the seafloor directly beneath the farm (Newell 2004; Mckindsey *et al.* 2011). Biodeposit accumulation depends on four main factors: (i) production rate, (ii) initial dispersal (hydrodynamic transport), (iii) redistribution once on the sediment surface (creep, saltation, resuspension, erosion) and (iv) rate of decay (Giles *et al.* ,2006, 2009; Mckindsey *et al.* 2011). In addition, rates vary among species, size and diet. Although smaller mussels produce a proportionally greater biodeposit quantity than larger ones, faeces are smaller having lower settlement rates due to their low density, thus being advected further afield by prevailing currents (Chamberlain 2002; Hartstein & Stevens 2005; Mckindsey *et al.* 2011). As mussel settle on the ropes during summer, small mussels dominate farm densities during highly hydrodynamic winter months producing higher amounts of low-density biodeposits that, although smaller in size, may be advected further afield.

Along with an increase in organic content and finer sediment, some authors have found reduced oxygen conditions beneath mussel farms. Other authors have drawn attention to the organisms associated with mussel farms and their contribution to the deposition of OM to the seafloor (Giles *et al.* 2006). Studies on highly hydrodynamic offshore mussel farms have found that the sediment beneath had no significantly greater OM content, carbon/nitrogen ratios or particle size than reference sites. Although an increase in biodeposits underneath the structure has been observed in certain developments, studies have found that physical and chemical changes reduce to natural levels approximately 30–300 m from the farm site, depending on the hydrodynamics of the area and the extent of the farm (Hartstein & Rowden 2004; Hartstein & Stevens 2005; Lacoste *et al.* 2018). Once on the seabed, biodeposits can either remain immobile due to lack of significant water movement on the sediment–water interface (Hartstein & Stevens 2005; Lin *et al.* 2016) or, given the right amount of energy, especially during storm seasons, biodeposits can be resuspended back into the ecosystem (Giles *et al.* 2009; Lin *et al.* 2016).

The reduction in tidal current horizontal velocity coupled with induced downwelling within offshore mussel farms can accelerate biodeposition, including both plankton and filter-feeding produced detritus (containing chlorophyll α), significantly affecting net biological processes (Giles *et al.* 2009; Lin *et al.* 2016). However, the different conditions of each farm site will produce different results and further studies as well as long-term monitoring programmes are needed to support this (Fabi *et al.* 2009).

Infaunal community changes/modifications. Benthic infauna not only rework sediments increasing oxygen penetration into the benthos but also enhance remineralisation of OM and through various bioturbation techniques, influence nutrient exchange rates between sediments and the water column (Callier *et al.* 2009). The magnitude of a farm's impact on benthic infauna communities is influenced by the farm (size, stocking density, age of development) and the site characteristics (hydrodynamic regime, bathymetry) (Hartstein & Rowden 2004; Hartstein & Stevens 2005; Lacoste *et al.* 2018). As communities may take 10–15 years to reach a new equilibrium following a disturbance (Mckindsey *et al.* 2011), if an offshore mussel farm is developed within heavily fished grounds, its impacts may be shadowed by the underlying effects of dredges and towed fishing gears.

Studies on offshore farms to date show either a reduction in infaunal densities (Hartstein & Rowden 2004), no effect on the meiofaunal abundance, taxa richness or community structure (Danovaro *et al.* 2004) or a combination of both (Lacoste *et al.* 2018). Overall, offshore mussel culture effects on benthic infaunal communities are usually limited in magnitude unless extreme conditions are given (poor flushing rates or exceeding densities) and fluctuations have been seen to be linked with natural seasonal and inter-annual rather than because of the mussel farm itself (Fabi *et al.* 2009; Lacoste *et al.* 2018). Impacts of offshore farms will then be tightly dependant on not only the hydrodynamics of the area but seasonal changes if any, and the type of habitat where the development is found. Ultimately, time, biodeposition loading and hydrodynamics will determine the degree of infaunal community modification (Chamberlain *et al.* 2001; Callier *et al.* 2008; Ysebaert *et al.* 2009; Lacoste *et al.* 2018).

Mobile macrofauna interactions. Mobile benthic fauna, including fish and crustaceans, can be affected by mussel aquaculture operations. The main mechanisms are as follows: (i) the addition of physical structure (anchor blocks or mussel fall-off), (ii) the provision of food from mussel fall-off or from other types of organisms growing on the longlines and farm infrastructure (Mckindsey *et al.* 2011; Keeley 2013; Callier *et al.* 2017) and (iii) the exclusion of other fishing activities (mobile and static gear) within the farm.

In a large development, mussel fall-off may be considerable, dramatically altering benthic habitats towards more heterogeneous hard-bottom biogenic reef-type communities. Mussels and shells have been found to cover 55% of the seafloor beneath offshore farms, substantially increasing the physical structure underneath. As mussels and associated epifauna fall from the aquaculture structures, build up and represent an attractive food source for benthic predators and scavengers (Figs 4,5; Inglis & Gust 2003; Mckindsey *et al.* 2011; Callier *et al.* 2017). Offshore farm studies report increased numbers and/or greater biomass of macrofauna such as crabs, lobsters and sea stars within farm sites, relative to control sites pointing to an increase in predatory organisms beneath the mussel ropes (Lacoste *et al.* 2018).

Although the knowledge of additional seafloor physical structure associated with offshore aquaculture is very limited, there is considerable literature on the importance of artificial structures (specially offshore wind farms), enhancing mobile macrofauna communities, operating as reefs (Inger *et al.* 2009; Callier *et al.* 2017; Heery *et al.* 2017). Much can be extrapolated from the relevant artificial reef (AR) literature where other types of communities may develop under and around the blocks supporting farms (Mckindsey *et al.* 2011; Callier *et al.* 2017). Hard-bottom-associated species that may otherwise not be there due to a lack of suitable habitat (e.g. offshore muddy bottoms or deep waters) or as a consequence of years of dredging and towing for commercial fisheries can now colonise these structures and the surrounding ecosystem forming communities that are functionally similar to hard-bottom habitats (Fig. 2; Inglis & Gust 2003; Mckindsey *et al.* 2011; Callier *et al.* 2017; Lacoste *et al.* 2018). As hard-bottom communities often are more diverse and have greater biomass and higher productivity than soft-bottom ones, this

Figure 4 ROV Videoray footage showing how the seabed underneath an offshore longline mussel farm (Lyme Bay, UK) is being utilised by commercially valuable crustaceans and fish (Mascorda Cabre 2020).

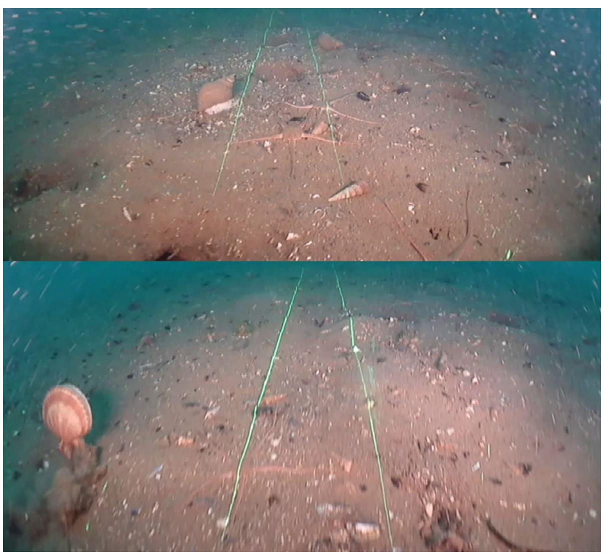

Figure 5 ROV Videoray footage showing how the seabed underneath an offshore longline mussel farm (Lyme Bay, UK) is being utilised by echinoderms and commercially valuable molluscs and gastropods such as scallops and whelks (Mascorda Cabre 2019).

can have a knock-on effect on the complexity of the habitat and even increase local diversity and productivity (Mckindsey *et al*. 2011).

Pelagic ecology

Compared to benthic habitats, there is very little research on the effects of mussel farming on pelagic ecosystems with no studies on the effects of offshore mussel farms therefore, the following section aims to extrapolate what is known from other mussel farms in order to understand the importance of this issue and the need for research on the topic.

Although most research focuses on mussel farm effects on the water column chemistry and plankton communities (La Rosa *et al*. 2002; Cranford *et al*. 2008; Trottet *et al*. 2008; Froján *et al*. 2018), recent attention has been given to farms attracting pelagic fish and vagile macroinvertebrates as well as interacting with planktonic communities (Figs 6,7). Additionally, organisms growing among mussel longlines and other farm structures such as algae and invertebrate organisms (epifauna) may also attract such organisms (Mckindsey *et al*. 2011; Callier *et al*. 2017).

Shellfish farms have been identified to affect nearby fishery resources through three possible interactions: (i) attraction or displacement of adults, (ii) recruitment reductions through the direct consumption of eggs and larvae and (iii) food web effects. Farms can have a wide range of direct and indirect effects on the organisms at both individual and population level, this in turn have implications for the management of fisheries and their ecosystems (Gibbs 2004).

Offshore mussel farms as fish aggregation devices. Offshore longline mussel farms not only add structure to the seabed in the form of anchor blocks and mussel fall-off, but add physical structure to the water column (buoys, ropes, etc.) where otherwise would be absent (Figs 2,4–7; Cornelisen 2013; Callier *et al*. 2017). Floating structures occurring in the open ocean are known to attract pelagic fish, widely recognised to act as fish aggregation devices (FADs;

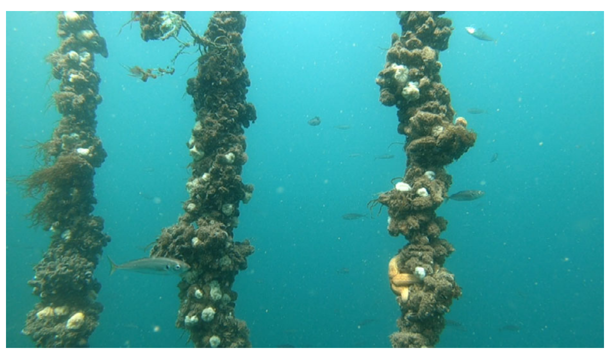

Figure 6 Schools of fish have been captured in an offshore longline mussel farm in Lyme Bay, South West UK. Picture has been taken from the recording of a non-baited midwater video (NMW) rig placed at 6 m depth. Longline ropes are full of mussels and biofouling (Mascorda Cabre 2020).

Figure 7 School of mullets have been captured in an offshore longline mussel farm in Lyme Bay, South West UK. Picture has been taken from the recording of a non-baited midwater video (NMW) rig placed at 6 m depth. Longline ropes are full of mussels and biofouling (Mascorda Cabre 2019).

Kingsford 1993; Nelson 2003; Matarazzo Suplicy 2018). As many studies have found that wild fish are attracted to aquaculture developments (Cornelisen 2013; Callier *et al.* 2017), farms are being thought to be acting as FADs due to the physical structure (Carpenter *et al.* 2009; Keeley *et al.* 2009; Clavelle *et al.* 2018) and its overall cascading effect.

Longline mussel farms offer a three-dimensional habitat for other organisms such as macroalgae, bryozoans or tunicates by providing substrate, food source and refuge from predation and adverse environmental conditions (Gutiérrez *et al.* 2003; Clavelle *et al.* 2018). Consequently, providing a direct food source for other predators, making farms attractive to higher food web organisms such as pelagic fish and other vagile organisms (Mckindsey *et al.* 2011; Callier *et al.* 2017).

Offshore farm observations in France and New Zealand report how the introduction of mussels to the area was followed by an increase in dominant fish species densities, some of which with commercial value. Pelagic species were found to be more common in the vicinity of the farm than in open water. Some were feeding on the mussels due to an increase in prey availability and others, including juveniles, were swimming through the longlines concluding that schools of fish could be attracted to the structure for shelter, refuge and nursery (Gerlotto *et al.* 2001; Brehmer *et al.* 2003; Keeley *et al.* 2009; Mckindsey *et al.* 2011).

Observations of birds and mammals interacting with suspended mussel farm structures show a positive or neutral effect on such species (Roycroft *et al.* 2007; Keeley *et al.* 2009; Clement 2013). Although studies on the interactions of seabirds and marine mammals with inshore mussel longlines found no significant difference in overall species richness and diversity between mussel farm and control sites, significantly higher numbers of seabirds heavily used mussel buoys as perching platforms for preening (Roycroft *et al.* 2007; Clement 2013). Some authors have stressed the potential for issues suggesting that interactions with marine mammals should not be overlooked as there is considerable uncertainty in the long-term and ecosystem-wide consequences, especially with the expansion of the industry in terms of scale and into the offshore environment. However, interactions are thought to be low risk as threats mainly arise from loose ropes or the site overlapping with migratory routes which can be easily echolocated (Keeley *et al.* 2009; Gentry *et al.* 2016; Callier *et al.* 2017; Matarazzo Suplicy 2018).

Modifications of the mesoplankton community. Longline mussel aquaculture places the bivalves in direct contact with the pelagic food web (Grant *et al.* 2008; Maar *et al.* 2008; Mckindsey *et al.* 2011). Due to their extensive filtration activity and grazing (Spencer 2002), large numbers of bivalve filter feeders like *Mytilus* sp. lead to ecosystem changes as they remove large quantities of phytoplankton and nutrients from the water column enhancing a 'top-down' control of planktonic communities within aquaculture areas (Prins *et al.* 1997; Lehane & Davenport 2002, 2006; Petersen 2004; Hulot *et al.* 2018; Grant & Pastres 2019). Shape and composition of particles play a role in the shaping of the mesoplankton community. During the filtration process, mussels tend to select larger cells as available. Coupled with an increased fertilisation through faeces and pseudofaeces, primary production is stimulated, shifting the system towards a dominance of smaller planktonic species within the water column of the aquaculture development (Strohmeier *et al.* 2012; Hulot *et al.* 2018). Within inshore farms, a significant depletion of larger species (zooplankton) is induced (Grant *et al.* 2008; Maar *et al.* 2008; Mckindsey *et al.* 2011) and food resources available to other organisms are shifted, altering the overall ecological carrying capacity of the area (Jiang & Gibbs 2005; Sequeira *et al.* 2008).

As the farm interacts with water currents reducing flows, the residence time of planktonic organisms increases, increasing their exposure to consumption, which can reduce both the biomass and production of plankton, described to be one of the main drivers of planktonic variability (Ferreira *et al.* 2007; Hulot *et al.* 2018). In a bay where the drag of an offshore mussel farm raft amplified water residence times, an increase in seston depletion was seen (Newell & Richardson 2014). A phytoplankton study spatially monitoring chlorophyll α (chl-α) concentrations in an offshore longline mussel farm in China reported a drastic decrease of up to 80% in surface chl-α concentration (Lin *et al.* 2016). Such a dramatic depletion can be further exacerbated by tides and stratification, becoming more serious during neap tides, especially during periods of low phytoplankton biomass (i.e. winter and summer; Lin *et al.*

2016). Additionally, a relatively high value of chl-α in the water below the submerged longline aquaculture coupled with salinity and temperature measurements showed an evident downward trend of water flow (Lin *et al.* 2016). This is further supported by a study performed in Italy observing how total phosphorus content reached highest concentrations underneath a farm (Rampazzo *et al.* 2013) illustrating the impact that hydrodynamic effects of the farm may have (Fig. 2).

Management, policy and offshore aquaculture conservation

Although the move of the industry offshore may ease some of the inshore space usage conflicts, the development of large offshore farms may occupy historically fished areas causing particular distress among certain parts of the fishing community (Keeley *et al.* 2009; Upton & Buck 2010; Fairbanks 2016). This can be in turn offset by an increase use of the area by recreational and other commercial fishers benefiting from the farm's FAD effect, especially during harvest due to fouling organisms from mussels and mussel lines (Keeley *et al.* 2009; Clavelle *et al.* 2018). The exclusion of fishing activities (mobile and static gear) from farmed grounds may not only provide the potential to enhance both commercial and non-commercial species producing a spill over effect but also present the prospect for benthic habitats to be restored to previous state (Halpern *et al.* 2009; Clavelle *et al.* 2018; Sheehan *et al.* 2019). In terms of conservation, this has been seen to be serving as a *de facto* marine protected areas (MPAs; Halpern *et al.* 2009; Clavelle *et al.* 2018; Sheehan *et al.* 2019).

As marine biodiversity continues to decline and with it the ecosystem services we so depend on, it is paramount to reconcile nature conservation and the sustainable development of the oceans (Le Gouvello *et al.* 2017; Sala *et al.* 2018; European Commission 2019). If we want to at least try to meet international marine conservation targets such as the Convention on Biological Diversity's (CBD) Aichi Target 11 (marine biodiversity protection) and Target 6 (sustainable fisheries) by 2030, and the Sustainable Development Goals (SDGs) 2 (food security and zero hunger) and SDG 14 (conservation and sustainable development) within the UN's 2030 Agenda (Convention on Biological Diversity, 2010, 2020; United Nations 2015; Le Gouvello *et al.* 2017; Sala *et al.* 2018; Duarte *et al.* 2020), the Blue Economy and in particular aquaculture as the fastest growing food industry in the world, must move forward together (Ferreira *et al.* 2009; Blanchard *et al.* 2017; Froehlich *et al.* 2017a; Matarazzo Suplicy 2018).

In order to meet international targets, the global number of MPAs has grown exponentially over the past decade, a vast amount of which allow extraction of resources being designated as 'partially protected areas' (PPAs; Horta e Costa *et al.* 2016; Sala *et al.* 2018; Singh *et al.* 2018; Zupan *et al.* 2018). Some literature reports that while no-take MPAs are the most effective tool to restore and conserve biodiversity, the greatest number of PPAs have no different protection than non-MPAs (Edgar *et al.* 2014; Sala *et al.* 2018; Claudet *et al.* 2020; Galparsoro *et al.* 2020; Rees *et al.* 2020). Nevertheless, other authors report that highly and moderately regulated PPAs are effective compared to unprotected areas. When placed adjacent to fully protected MPAs, highly regulated PPAs can enhance their ecological benefits and in turn, increase their ecosystem service outcomes (Zupan *et al.* 2018). It could be argued that compared to some PPAs, offshore mussel farms provide more biodiversity protection than non-managed MPAs. For instance, offshore mussel farming might be preferable to other destructive extractive activities (Le Gouvello *et al.* 2017) such as trawl fishing already happening in multi-use MPAs (Sala *et al.* 2018). In particular, for MPA-communities it not only provides food security and economic resilience but it presents as a sustainable alternative to overfishing (Le Gouvello *et al.* 2017; Sala *et al.* 2018).

Following the six IUCN's categories of MPAs, the most used Categories V and IV (multi-purpose) already allow certain aquaculture activities (Day *et al.* 2012) while all but Category I, may allow some type of aquaculture (Le Gouvello *et al.* 2017). As the world is far from achieving the UN's marine conservation targets of protecting 10% of the oceans by 2020 (now updated to 30% in 'highly protected' areas by 2030; Convention on Biological Diversity 2020), we must grasp every chance we have to truly protect and restore biodiversity at all levels as long as management and regulations are in place, well implemented and enforced (Sala *et al.* 2018). The CBD's zero-draft report (Convention on Biological Diversity 2020) highlights that as part of the new 2030 and 2050 Goals, we must meet people's food security and livelihood needs through a sustainable use of the oceans by conserving and enhancing biodiversity in managed ecosystems. Misinterpretation of IUCN's guidelines is common (Horta e Costa *et al.* 2016) thus, for a well-developed joint aquaculture conservation venture, designated areas need clear conservation objectives along with detailed information on resource extraction, management plans and implementation and enforcement (Sala *et al.* 2018; European Commission 2019).

New guidance from IUCN to support achieve CBD Aichi Target 11 has described 'other effective area-based conservation measures' (OECMs) as an important tool alongside MPA designation (Convention on Biological Diversity 2018). Although creation and governance might be different to well-managed MPAs, the underlying principles and ultimate goals of OECMs should result in the same outcomes providing yet another opportunity for aquaculture conservation cooperation delivering socio-economic as well as ecological benefits (Sala *et al.* 2018; Rees *et al.* 2020). To achieve the UN's SDGs, the remaining 70% (if 30% of the oceans are protected by 2030) of our seas should be managed sustainably (Rees *et al.* 2020). If we ought to conserve biodiversity and protect ecosystem services, we must go beyond the use of MPAs or PPAs. OECMs within a wider range of natural resource management interventions are needed to contribute to the development of wider governance conservation frameworks (FAO 2018; Rees *et al.* 2020). In addition to no-take-zones, we need every area that protects biodiversity at any level (FAO 2018; Sala *et al.* 2018) to meet the right environmental, social and economic sustainability goals.

A clear opportunity to enhance offshore aquaculture and conservation (FAO 2018; Galparsoro *et al.* 2020; Rees *et al.* 2020) is the implementation of an ecosystem-based approach for aquaculture (EAA) proposed (Soto *et al.* 2008; FAO 2018) to be at the forefront of Blue Growth goals in conservation aquaculture for the planning, development and management of the industry (Froehlich *et al.* 2017a; FAO 2018; Klinger *et al.* 2018; European Commission 2019) providing fundamental area-based frameworks (FAO 2018; Galparsoro *et al.* 2020). This must be developed in a context of connectivity and co-location through tools like MSP which integrate management of land, water and other resources enabling a sustainable growth of the industry minimising conflict, integrating clear social, economic and environmental objectives (FAO 2018; Galparsoro *et al.* 2020; Rees *et al.* 2020). However, in the case of offshore aquaculture, EAA efforts are hindered by lack of research, knowledge and guidelines which must be supported with effective governance (Le Gouvello *et al.* 2017; Weitzman 2019). Economic benefits may be more likely to materialise if planned and performed appropriately (European Commission 2019).

Discussion

Even though offshore mussel farming has the potential to be a great sustainable source of protein, it still remains well below its production potential. It has been argued that the main reasons are due to negative public perception affecting the market, long and difficult licensing procedures, lack of clear policy and management, space constrains and environmental and economic factors (Kapetsky *et al.* 2013; Fairbanks 2016; Matarazzo Suplicy 2018; European Commission 2019; Galparsoro *et al.* 2020). Improvement of governance with the establishment of adequate legislative frameworks, simplified administrative procedures along the promotion of the industry as a sustainable practice are paramount to minimise conflicts and environmental impacts for the sustainable development of the industry offshore (Matarazzo Suplicy 2018; European Commission 2019; Galparsoro *et al.* 2020).

Understanding the interactions of offshore longline mussel farms with the hydrodynamic regime of the area can help determine the extent of ecological effects. The available literature shows that a vast amount of knowledge and research gaps concerning offshore aquaculture-environment interactions exist, which are needed to inform management and legislation as well as to understand and assess ecological benefits and consequences.

As few studies include pre-development data relying on the comparison between farm sites and reference locations, the authors highlight the need to include baseline studies as well as long-term monitoring of marine systems to fully understand natural, temporal and spatial variations that may otherwise disguise underlying anthropogenic disturbances (Underwood 1990; Mckindsey *et al.* 2011; Upton & Buck 2010; Callier *et al.* 2017).

The identified below priorities should be focused on offshore longline mussel farms in order to help the industry develop and be part of a sustainable 'Blue Revolution' as part of the 'Blue Growth Agenda' with objectives such as the development of smart green aquaculture and biodiversity conservation as part of an EAA (Soto *et al.* 2008; Upton & Buck 2010; Hambrey & Evans 2016; Froehlich *et al.* 2017a; FAO 2018; Klinger *et al.* 2018; European Commission 2019; Smaal *et al.* 2019).

Influence of the farm on water flow

To date, studies have focused on either ecological or oceanographic effects of mussel farms with the majority concentrating on describing the latter through numerical modelling though lacking the link between the two (Plew *et al.* 2005). In light of preliminary evidence, models suggest that hydrodynamic regimes play a crucial role in understanding offshore aquaculture-environment interactions, providing an important insight into the behaviour of background oceanographic currents when in contact with a porous structure like that of an offshore farm (Plew *et al.* 2005; Plew 2011; Stevens & Petersen 2011; O'Donncha *et al.* 2013, 2016; Newell & Richardson 2014; Gagnon & Bergeron 2017; Chen *et al.* 2019). This is crucial as any change in the background currents due to the establishment of a farm happens before any other interaction and will determine nutrient and organic loading transport and therefore, the extent of any other impacts, especially the dispersion of biodeposits which in turn will determine the overall knock-on ecological effects (Stevens & Petersen 2011; Lin *et al.* 2016).

Although recent theoretical, experimental, observational and numerical modelling studies have focused on the wave attenuation effect of canopies, full understanding of the alterations to the mean wave-driven currents and water flow are still limited, especially its links to particulate matter and water exchange rates through the canopy margins and water column (Chen *et al.* 2019) as well as its effects to resuspension of biodeposits due to increase velocities beneath the farm (Fabi *et al.* 2009; Plew 2013; Rampazzo *et al.* 2013). Ultimately, water flow modification and diversion depend on different factors such as bathymetry, density stratification, bottom friction, canopy density, proportion of water depth occupied as well as proximity to other developments and to the coast (Plew 2011).

Due to the high complexity of interactions between prevailing currents and biodeposits, representing spatio-temporal interactions at a farm-scale are difficult to predict and explain based on numerical models or laboratory based studies alone. Therefore, it is important to reflect the reality of such with more *in situ* studies. In particular, further detailed field studies undertaking extensive investigations of mean wave-driven currents and water flow modification measurements are needed to better understand alterations to the current and turbulence structure, validate models through critical observations to resolve existing gaps on how offshore farms generate current and stratification distortions, wave attenuation and wake formation. This will ultimately help decipher offshore aquaculture-environment interactions to understand biodeposition and resuspension, nutrient depletion and how such hydrodynamic regimes and pathways influence the local ecology (Plew *et al.* 2005; Stevens & Petersen 2011; Lin *et al.* 2016) and overall ecosystem services capacity of the farm helping estimate consequent ecological impacts (Stevens *et al.* 2008; Plew 2013; Chen *et al.* 2019) and the farm's footprint (Plew *et al.* 2005, 2006; Tseung *et al.* 2016) in order to provide factual and effective MSP (Mckindsey *et al.* 2011; Plew 2013; FAO 2018; Klinger *et al.* 2018; Landmann *et al.* 2019).

Although currents are key agents for the industry, the questions of whether water flow will be diverted horizontally or vertically around the canopy and what effect stratification has on this still remain not fully understood (Plew *et al.* 2006). A range of indexes have been developed in order to calculate dispersal rates and times (Hartstein & Stevens 2005; McKindsey *et al.* 2006; Stevens *et al.* 2008; Callier *et al.* 2009; Cranford *et al.* 2009; Lovatelli *et al.* 2013) however these are far from being able to portrait a real image due to the complexity of an offshore longline mussel farm system.

In general, the spatial and temporal variability in currents induced by offshore longline structures requires more research at the small to medium (metres to hundreds of metres) scales (Plew 2013). Detailed field studies, in particular more research, is required, but not limited to:

- the magnitude and extent of overall water flow modification
- the magnitude and extent of a wake formation
- the magnitude and spatial scales of changes to water column processes such as stratification of density, temperature or nutrients, which influence vertical density variations affecting water flows and carrying capacity around the structures
- whether the structures induce significant vertical mixing
- whether different longline stocking densities or designs and orientation to the water flow significantly alter wave and current attenuation
- if refraction (changes in the direction of wave propagation) or reflection of waves occurs
- the extent and importance of fouling which can change the drag of shellfish structures through smothering and decreasing drag
- interaction between the seabed (bottom boundary layer) and the bottom of the farm (biodeposition and resuspension)
- hydrodynamic and physicochemical model validation
- how the above can be best utilised to engineer the most efficient farm design and outlay

Ecological interactions

There is insufficient information to widely support the statements that ecological effects of offshore mussel farms (i) are limited to restricted areas, (ii) have no significant impacts on benthic and pelagic habitats and species or (iii) biodeposit effects are minimal due to dispersal by high hydrodynamic flows. It is clear that long-term monitoring of marine benthic and pelagic systems is needed in order to fully understand natural temporal and spatial variations that may disguise anthropogenic disturbances (Fabi *et al.* 2009; Mckindsey *et al.* 2011; Lacoste *et al.* 2018).

Although biodeposit production data and hydrodynamic modelling have been coupled to investigate and predict the benthic loading footprint of mussel farms (Giles *et al.* 2009; Weise *et al.* 2009), there are still important gaps in knowledge in respect to net biological process and biodeposition (Hartstein & Rowden 2004; Hartstein & Stevens 2005; Giles *et al.* 2009; Lin *et al.* 2016; Lacoste *et al.* 2018). Studies support the strong relationship between the hydrodynamic regime of a farm site, OM enrichment in seabed sediments by biodeposits, and a subsequent modification of infauna and macrofauna (Hartstein & Stevens 2005; Lin *et al.* 2016; Lacoste *et al.* 2018).

While there is a lack of studies on the impacts of offshore developments, it is clear that the shifting baseline from a soft-bottom to a hard-bottom like habitat and the consequent increase in food availability can attract the attention of mobile macrofauna and even shift diets of organisms (Callier *et al.* 2007; Mckindsey *et al.* 2011; Lacoste *et al.* 2018). This coupled with the exclusion of mobile fishing gear within the farm providing safe ground for species to colonise the restored habitat opens a window to the need of further investigation in order to understand if an offshore mussel farm could potentially develop macrofaunal communities (Inglis & Gust 2003; Mckindsey *et al.* 2011; Callier *et al.* 2017) where otherwise would be bare ground with the implications that this can have to commercial species.

It is still uncertain the mechanisms behind the FAD effect of mussel farms. This review recommends further studies to clarify if it is due to the fish being attracted by the added physical structure or enhanced by it, the shift to a more complex hard substrate, the farmed product itself, the associated organisms, the refuge given by the mussel matrix or a combination of these (Keeley *et al.* 2009; Mckindsey *et al.* 2011; Callier *et al.* 2017). The different mechanisms by which species are attracted (or repelled) and the subsequent direct and indirect effects at the individual and population levels are also unknown but important to study (Callier *et al.* 2017; Clavelle *et al.* 2018) in terms of interactions with nearby fisheries, recreational fishing, MPAs and in a management perspective. Ultimately, the significance of the argument relies on the uncertainty of whether the FAD effect is attracting fish communities aggregating from elsewhere or it is enhancing the population and whether it is in turn favouring particular species altering the existing fish assemblages and the community overall (Keeley *et al.* 2009). Nonetheless, it is yet unknown whether this increase may have positive or negative effects on the wider population (Keeley *et al.* 2009).

Some studies have investigated the potential modification of the mesoplankton community by mussel farms (Lehane & Davenport 2002; Hulot *et al.* 2018) as well as chl-α concentration alterations in offshore developments (Lin *et al.* 2016). As levels of sestonic depletion by mussel farms are highly variable throughout the literature, especially due to seasonal variations (Strohmeier *et al.* 2008; Hulot *et al.* 2018) it is clear that not all planktonic populations would benefit from the hydrodynamic effects of an offshore mussel farm and any alterations in residence time in the same way. When studying the effects of an offshore mussel farm on the planktonic community, it is important to account for the different mechanisms involved in this complex process, from an enhancement of plankton residence time to alterations due to seasonal stratifications.

Most studies have mainly been done under laboratory conditions with no field validations and in most cases, low numbers of mussels have been used. This is far from representative of a large offshore mussel farm and it is unlikely that results can be extrapolated due to the variety of factors at stake. Although recent studies have made significant progress on understanding such complexity, efforts must continue to focus on, but not limited to, research to understand:

- biodeposit quantity, quality and its decay rates (OM content of faeces and pseudofaeces)
- biodeposition dispersal
- redistribution and resuspension of biodeposits in the environment following initial deposition to the seafloor. This is thought to be crucial in areas with strong currents
- changes in sediment physicochemical parameters after biodeposition
- whether different longline stocking densities or designs and orientation to the water flow have an impact on the above ecological effects
- whether different bathymetry and underlying environmental characteristics of the area such as depth, habitat types or climate have an impact on the above ecological effects
- investigating the role of the epibiont community
- studying functional change of planktonic communities due to mussel predation and residence time alteration

Management, policy and conservation

It may seem strange to most to have conservation and aquaculture in the same sentence, let alone complementing each other as for many, aquaculture is mainly an undesirable industry following coastal aquaculture's long resume of environmental impacts (Fairbanks 2016; Froehlich *et al.* 2017a; Le Gouvello *et al.* 2017). While true, the industry has dramatically changed in the last 20 years (Froehlich *et al.* 2017a), but public perception on the industry's reputation has yet to catch up. Changes in practices and improved technology have shifted the role that aquaculture can have in conservation (Froehlich *et al.* 2017a; Le Gouvello *et al.* 2017), biogenic reef habitat (shellfish reef) restoration (Froehlich *et al.* 2017a; Le Gouvello *et al.* 2017; Alleway *et al.* 2019; Zu Ermgassen *et al.* 2020) and as a crucial sustainable source of protein (FAO 2016; Hilborn *et al.* 2018; Matarazzo Suplicy 2018).

Rope-grown mussel cultivation has been shown to be compatible with MPA objectives; with growing evidence and guidelines on how the blue economy sector can contribute to conservation through the creation of *de facto* refuges, this industry has the potential to add the economic benefits of conservation to its list of ecosystem service benefits. With the prospective to recover damaged habitats, boost ecosystem services and benefit biodiversity if effectively managed, offshore mussel farms may have the ability to become part of a wider marine conservation strategy as OECMs (Convention on Biological Diversity 2018; Rees *et al.* 2020). However, more empirical evidence is needed to support this and move away from the perception that aquaculture is excluding other activities often seen as costs to other blue economic sectors (Froehlich *et al.* 2017a; Haines *et al.* 2018). Thus the need to clearly understand the objectives of MPAs and aquaculture to establish positive and negative synergies (Froehlich *et al.* 2017a; Le Gouvello *et al.* 2017) having at its core an integrated ecosystem-based approach (Sala *et al.* 2018; Rees *et al.* 2020).

Although some argue that sustainable fisheries and conservation should not be merged, they are complementary (Sala *et al.* 2018) requiring an integrated ecosystem-based approach to management (Solandt *et al.* 2020) where offshore aquaculture can be a part of the solution. Offshore mussel farming has the potential to enhance fisheries by achieving sustainable resource extraction within a healthy ocean (Froehlich *et al.* 2017a; Le Gouvello *et al.* 2017; Clavelle *et al.* 2018; FAO 2018; Sheehan *et al.* 2019) throughout a mosaic of interconnected ecological ‘corridors’ (Solandt *et al.* 2020). Though, we must keep in mind that there’s a distinction between biodiversity focused areas and areas important for the ecosystem services they provide which do not always share the same objectives (Rees *et al.* 2020).

The implementation of conservation regulations and ecological effectiveness are mutualistic hence the need to invest in management, control and enforcement as a priority (Edgar *et al.* 2014; Zupan *et al.* 2018; Duarte *et al.* 2020; Solandt *et al.* 2020). Research has demonstrated that age and size of any marine conservation designation and the number and type of extraction activities allowed is correlated to its success (Edgar *et al.* 2014; Zupan *et al.* 2018). To ensure the sustainable management of offshore aquaculture, an understanding of environment-activity interactions is required (Kapetsky *et al.* 2013; Stelzenmüller *et al.* 2013; Callier *et al.* 2017; Strand *et al.* 2017; Lacoste *et al.* 2018; Lester *et al.* 2018; Landmann *et al.* 2019; Galparsoro *et al.* 2020) thus, the need to provide rigorous advice on the feasibility of co-locating offshore aquaculture with other blue economy developments in a context of marine conservation (Sheehan *et al.* 2019).

Managers, scientists, users and conservationists have a role to play on the success of MPAs in a context of increasing expansion of societal demands into the ocean therefore, biodiversity conservation must embrace sustainable economic activities (Le Gouvello *et al.* 2017). In particular, it is paramount to improve our understanding on:

- offshore aquaculture-environment interactions and overall footprint
- rigorous advice on MSP and co-location of offshore aquaculture with other blue economy developments and MPA designation
- cooperation of offshore aquaculture and MPAs conservation objectives, resource extraction and management plans

Conclusions

The growing demand for aquatic protein suggests that aquaculture will continue to grow with bivalve farming playing a crucial role as an efficient and ecologically viable option. The increasing interest to move large-scale developments into the offshore environment has made this an innovative and attractive research field that requires creative solutions to address the challenges of such a dynamic environment.

This review has shown that offshore longline mussel aquaculture can have a myriad of influences from water currents to benthic and pelagic communities. After a thorough examination on (i) the effect of farms on background oceanography and (ii) the consequent ecological effects and response, it can be said that farm-scale changes in currents are almost certain with interactions at local, bay-wide and regional scales. Impacts of large offshore farms on the local hydrodynamic regime are highly likely and preliminary evidence indicates that the orientation and spacing of structures has an important effect and can induce spatial variations in currents. Thus, farm size (farm structures and layout) and farm location informs the intensity of the aquaculture-environment interactions which may decrease with distance from the farm.

While physical interactions have direct consequences such as the attenuation of wave energy, the formation of a wake and the effect on stratification, this review described the importance of physical effects on ecological processes such as an increase in material and plankton residence times which can increase biodeposition and seston depletion, modify the benthic habitat and promote the farm as a FAD. It is clear that the relationship between the physical and ecological systems lacks understanding. Although physical effects on currents will persist for the duration that the structures and crop are in place, return to ambient conditions on removal will be nearly immediate. On the contrary, ecological consequences of modified currents may not be seen instantaneously but appreciated gradually and persist for longer.

Although the (iv) main knowledge gaps highlighted a range of research priorities, the authors consider that priority and importance should not only be driven by lack of knowledge or scientific interest but also socio-ecological and management needs. Mussel farming offers a variety of ecosystem services each of which has some intrinsic value. A mussel farm’s ‘positive’ or ‘negative’ influence on the system depends on what has been used to weigh the different factors which can be moved either side of the balance following fickle societal values. Thus, the idea of promoting a threshold of acceptable change should be evaluated at a site by site basis. With the compel to move towards ecosystem-based management, it might be appropriate to consider trade-offs between not only what can be perceived as environmental 'negative' or 'positive' impacts but where and how research efforts are targeted depending on their absolute suitability.

In the context of promoting sustainable practices through (iii) management, policy and conservation, it is important to have a coexistence of marine resource exploitation and smart environmental management hence, the idea of co-use of marine waters by aquaculture and other sectors and co-management in terms of environmental conservation has lately become more tangible with new legislation. Coupling offshore mussel farms with marine conservation with the idea of using them as *de facto* MPAs, particularly as OECMs, may have a decisive role to play in complementing stricter conservation measures. Although combining offshore longline mussel farms with conservation or as an integrative approach (EAA) with large-scale developments poses a challenge, it is paramount that we continue this research to better describe the oceanographic and ecological interactions to understand how they can be minimised as future policy will depend on it.

To avoid repetition of the so-called 'race to fish' with a 'rush to farm offshore', more information is crucial to underpin policies, strategic decisions and inform management measures needed to make sure that the offshore aquaculture expansion does not arise an array of impacts but rather an increased sustainable harvest. Offshore mussel aquaculture has the potential to be one of the most environmentally sustainable industries but it will need governance support to be able to deliver the right conservation measures through the right regulations. Ultimately, it has the capacity to play a crucial role in the future of our oceans and livelihoods.

Acknowledgements

The authors would like to thank Offshore Shellfish Ltd. for funding this work and providing knowledge and insights into offshore aquaculture practices. The authors are grateful to the editor and four anonymous reviewers for their valuable comments that improved this review.

Funding

All authors have contributed significantly to this work funded by Offshore Shellfish Ltd.

References

Alleway HK, Gillies CL, Bishop MJ, Gentry RR, Theuerkauf SJ, Jones R (2019) The ecosystem services of marine aquaculture: valuing benefits to people and nature. *BioScience* **69**: 59–68.

Aure J, Strohmeier T, Strand Ø (2007) Modelling current speed and carrying capacity in long-line blue mussel (*Mytilus edulis*) farms. *Aquaculture Research* **38**: 304–312.

Aypa SM (1990) Chapter 4. Mussel culture. *Food and Agriculture Organization of the United Nations (FAO)*. [Cited 11 Jan 2019.] Available from URL: http://www.fao.org/3/ab737e/AB737E04.htm.

Bendell LI (2014) Community composition of the intertidal in relation to the shellfish aquaculture industry in coastal British Columbia, Canada. *Aquaculture* **433**: 384–394.

Blanchard JL, Watson RA, Fulton EA, Cottrell RS, Nash KL, Bryndum-Buchholz A *et al*. (2017) Linked sustainability challenges and trade-offs among fisheries, aquaculture and agriculture. *Nature Ecology and Evolution* **1**: 1240–1249.

Boyd AJ, Heasman KG (1998) Shellfish mariculture in the Benguela system: water flow patterns within a mussel farm in Saldanha Bay, South Africa. *Journal of Shellfish Research* **17**: 25–32.

Brehmer P, Gerlotto F, Guillard J, Sanguinède F, Guénnegan Y, Buestel D (2003) New applications of hydroacoustic methods for monitoring shallow water aquatic ecosystems: the case of mussel culture grounds. *Aquatic Living Resources* **16**: 333–338.

Brenner M, Ramdohr S, Effkemann S, Stede M (2009) Key parameters for the consumption suitability of offshore cultivated blue mussels (*Mytilus edulis* L.) in the German Bight. *European Food Research and Technology* **230**: 255–267.

Buck BH (2007) Experimental trials on the feasibility of offshore seed production of the mussel *Mytilus edulis* in the German Bight: installation, technical requirements and environmental conditions. *Helgoland Marine Research* **61**: 87–101.

Buck BH, Thieltges DW, Walter U, Nehls G, Rosenthal H (2005) Inshore-offshore comparison of parasite infestation in *Mytilus edulis*: implications for open ocean aquaculture. *Journal of Applied Ichthyology* **21**: 107–113.

Buck BH, Troell MF, Angel DL, Chopin T, Krause G, Grote B (2018) State of the art and challenges for offshore integrated multi-trophic aquaculture (IMTA). *Frontiers in Marine Science* **5**: 1–21.

Callier MD, Byron CJ, Bengtson DA, Cranford PJ, Cross SF, Focken U *et al*. (2017) Attraction and repulsion of mobile wild organisms to finfish and shellfish aquaculture: a review. *Reviews in Aquaculture* 1–26.

Callier MD, McKindsey CW, Desrosiers G (2007) Multi-scale spatial variations in benthic sediment geochemistry and macrofaunal communities under a suspended mussel culture. *Marine Ecology Progress Series* **348**: 103–115.

Callier MD, McKindsey CW, Desrosiers G (2008) Evaluation of indicators used to detect mussel farm influence on the benthos: two case studies in the Magdalen Islands, Eastern Canada. *Aquaculture* **278**: 77–88.

Callier MD, Richard M, McKindsey CW, Archambault P, Desrosiers G (2009) Responses of benthic macrofauna and biogeochemical fluxes to various levels of mussel biodeposition: an *in situ* "benthocosm" experiment. *Marine Pollution Bulletin* **58**: 1544–1553.

Callier MD, Weise AM, McKindsey CW, Desrosiers G (2006) Sedimentation rates in a suspended mussel farm (Great-Entry Lagoon, Canada): biodeposit production and dispersion. *Marine Ecology Progress Series* **322**: 129–141.

Carpenter SR, Mooney HA, Agard J, Capistrano D, DeFries RS, Díaz S *et al*. (2009) Science for managing ecosystem services: Beyond the Millennium Ecosystem Assessment Stephen. *PNAS* **106**: 1305–1312.

Chamberlain J (2002) *Modelling the environmental impacts of suspended mussel (Mytilus edulis L.) farming*. Napier University. [Cited 11 Jan 2019.] Available from URL: https://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.251351.

Chamberlain J, Fernandes TF, Read P, Nickell TD, Davies IM (2001) Impacts of biodeposits from suspended mussel (*Mytilus edulis* L.) culture on the surrounding surficial sediments. *ICES Journal of Marine Science* **58**: 411–416.

Chen H, Liu X, Zou Q-P (2019) Wave-driven flow induced by suspended and submerged canopies. *Advances in Water Resources* **123**: 160–172.

Claudet J, Loiseau C, Sostres M, Zupan M, Claudet J, Loiseau C *et al*. (2020) Underprotected marine protected areas in a global biodiversity hotspot. *One Earth* **2**: 380–384.

Clavelle T, Lester SE, Gentry R, Froehlich HE (2018) Interactions and management for the future of marine aquaculture and capture fisheries. *Wiley* **20**: 368–388.

Clement D (2013) Effects on marine mammals. In: Sagar P (ed) *Literature Review of Ecological Effects of Aquaculture*, pp. 4.1–4.19. Ministry for Primary Industries, Cawthron Institute & National Institute for Water and Atmospheric Research Ltd, New Zealand.

Convention on Biological Diversity (2010) *Aichi biodiversity targets. Strategic plan 2011–2020*. [Cited 23 Apr 2019.] Available from URL: https://www.cbd.int/sp/targets/.

Convention on Biological Diversity (2018) *Protected areas and other effective area-based conservation measures (Decision 14/8)*. [Cited 23 Apr 2019.] Available from URL: https://www.cbd.int/doc/decisions/cop-14/cop-14-dec-08-en.pdf.

Convention on Biological Diversity (2020) *Zero draft of the post-2020 global biodiversity framework*. [Cited 23 Apr 2019.] Available from URL: https://www.cbd.int/doc/c/efb0/1f84/a892b98d2982a829962b6371/wg2020-02-03-en.pdf.

Cornelisen C (2013) Effects on wild fish. In: Ford R (ed) *Literature Review of Ecological Effects of Aquaculture*, pp. 5.1–5.14. Ministry for Primary Industries, Cawthron Institute & National Institute for Water and Atmospheric Research Ltd, New Zealand.

Cranford PJ, Hargrave BT, Doucette LI (2009) Benthic organic enrichment from suspended mussel (*Mytilus edulis*) culture in Prince Edward Island, Canada. *Aquaculture* **292**: 189–196.

Cranford PJ, Li W, Strand Ø, Strohmeier T (2008) *Phytoplankton Depletion by Mussel Aquaculture: High Resolution Mapping, Ecosystem Modeling and Potential Indicators of Ecological Carrying Capacity*. International Council for the Exploration of the Seas (ICES).

Crawford CM, Macleod CKA, Mitchell IM (2003) Effects of shellfish farming on the benthic environment. *Aquaculture* **224**: 117–140.

D'Amours O, Archambault P, McKindsey CW, Johnson LE (2008) Local enhancement of epibenthic macrofauna by aquaculture activities. *Marine Ecology Progress Series* **371**: 73–84.

Danovaro R, Gambi C, Luna GM, Mirto S (2004) Sustainable impact of mussel farming in the Adriatic Sea (Mediterranean Sea): evidence from biochemical, microbial and meiofaunal indicators. *Marine Pollution Bulletin* **49**: 325–333.

Day J, Dudley N, Hockings M, Holmes G, Laffoley D, Stolton S *et al*. (2012) *Guidelines for Applying the IUCN Protected Area Management Categories to Marine Protected Areas*. IUCN, Gland.

Delaux S, Stevens CL, Popinetl S (2011) High-resolution computational fluid dynamics modelling of suspended shellfish structures. *Environmental Fluid Mechanics* **11**: 405–425.

Dimitriou PD, Karakassis I, Pitta P, Tsagaraki TM, Apostolaki ET, Magiopoulos I *et al*. (2015) Mussel farming in Maliakos Gulf and quality indicators of the marine environment: good benthic below poor pelagic ecological status. *Marine Pollution Bulletin* **101**: 784–793.

Duarte CM, Agusti S, Barbier E, Britten GL, Castilla JC, Gattuso JP *et al*. (2020) Rebuilding marine life. *Nature* **580**: 39–51.

Duarte CM, Holmer M, Olsen Y, Soto D, Marbà N, Guiu J *et al*. (2009) Will the oceans help feed humanity? *BioScience* **59**: 967–976.

Duarte P, Labarta U, Fernández-Reiriz MJ (2008) Modelling local food depletion effects in mussel rafts of Galician Rias. *Aquaculture* **274**: 300–312.

Edgar GJ, Stuart-Smith RD, Willis TJ, Kininmonth S, Baker SC, Banks S *et al*. (2014) Global conservation outcomes depend on marine protected areas with five key features. *Nature* **506**: 216–220.

Ellis T, Gardiner R, Gubbins M, Reese A, Smith D *et al*. (2007) The EU Blue Economy Report 2019. *European Commission (2019)*. (Vol. 35) SEAFISH. [Cited 23 Oct 2019.] Available from URL: ftp://ftp.fao.org/docrep/fao/011/i0250e/i0250e.pdf.

European Commission (2019) *The EU Blue Economy Report 2019*. [Cited 23 Oct 2019.] Available from URL: https://op.europa.eu/en/publication-detail/-/publication/676bbd4a-7dd9-11e9-9f05-01aa75ed71a1/language-en/.

Fabi G, Manoukian S, Spagnolo A (2009) Impact of an open-sea suspended mussel culture on macrobenthic community (Western Adriatic Sea). *Aquaculture* **289**: 54–63.

Fairbanks L (2016) Moving mussels offshore? Perceptions of offshore aquaculture policy and expansion in New England. *Ocean and Coastal Management* **130**: 1–12.

FAO (2016) *The State of World Fisheries and Aquaculture 2016 – Contributing to Food Security and Nutrition for All*. Food and

Agriculture Organization of the United Nations. [Cited 11 Jan 2019.] Available from URL: http://www.fao.org/3/a-i5555e.pdf.

FAO (2018) *The State of World Fisheries and Aquaculture 2018 – Meeting the Sustainable Development Goals*. Food and Agriculture Organization of the United Nations. [Cited 11 Jan 2019.] Available from URL: ftp://ftp.fao.org/docrep/fao/011/i0250e/i0250e.pdf.

Ferreira JG, Hawkins AJS, Bricker SB (2007) Management of productivity, environmental effects and profitability of shellfish aquaculture – the Farm Aquaculture Resource Management (FARM) model. *Aquaculture* **264**: 160–174.

Ferreira JG, Hawkins AJS, Bricker SB (2011) The role of shellfish farms in provision of ecosystem goods and services. In: Shumway SE (ed) *Shellfish Aquaculture and the Environment*, pp. 3–31. John Wiley & Sons Inc, Singapore.

Ferreira JG, Sequeira A, Hawkins AJS, Newton A, Nickell TD, Pastres R *et al.* (2009) Analysis of coastal and offshore aquaculture: application of the FARM model to multiple systems and shellfish species. *Aquaculture* **292**: 129–138.

Froehlich HE, Gentry RR, Halpern BS (2017) Conservation aquaculture: shifting the narrative and paradigm of aquaculture's role in resource management. *Biological Conservation* **215**: 162–168.

Froehlich HE, Smith A, Gentry RR, Halpern BS (2017) Offshore aquaculture: I know it when I see it. *Frontiers in Marine Science* **4**: 154.

Froján M, Castro CG, Zúñiga D, Arbones B, Alonso-Pérez F, Figueiras FG (2018) Mussel farming impact on pelagic production and respiration rates in a coastal upwelling embayment (Ría de Vigo, NW Spain). *Estuarine, Coastal and Shelf Science* **204**: 130–139.

Gagnon M, Bergeron P (2017) Observations of the loading and motion of a submerged mussel longline at an open ocean site. *Aquacultural Engineering* **78**: 114–129.

Gallardi D (2014) Effects of bivalve aquaculture on the environment and their possible mitigation: a review. *Fisheries and Aquaculture Journal* **5**: 8.

Galparsoro I, Murillas A, Pinarbasi K, Sequeira AMM, Stelzenmüller V, Borja Á *et al.* (2020) Global stakeholder vision for ecosystem-based marine aquaculture expansion from coastal to offshore areas. *Reviews in Aquaculture* **12**: 2061–2079.

Gentry RR, Froehlich HE, Grimm D, Kareiva P, Parke M, Rust M *et al.* (2017) Mapping the global potential for marine aquaculture. *Nature Ecology & Evolution* **1**: 1317–1324.

Gentry RR, Lester SE, Kappel CV, White C, Bell TW, Stevens J *et al.* (2016) Offshore aquaculture: spatial planning principles for sustainable development. *Ecology and Evolution* **7**: 733–743.

Gerlotto F, Brehmer P, Buestel D, Sanguinede F (2001) A method for acoustic monitoring of a mussel longline ground using vertical echosounder and mutlibeam sonar. In: ICES Annual Science Conference Oslo, 26–29 September 2001, p. 14. International Council for the Exploration of the Sea.

Gibbs MT (2004) Interactions between bivalve shellfish farms and fishery resources. *Aquaculture* **240**: 267–296.

Gibbs MM, James MR, Pickmere SE, Woods PH, Shakespeare BS, Hickman RW *et al.* (1991) Hydrodynamic and water column properties at six stations associated with mussel farming in Pelorus sound, 1984–85. *New Zealand Journal of Marine and Freshwater Research* **25**: 239–254.

Giles H, Broekhuizen N, Bryan KR, Pilditch CA (2009) Modelling the dispersal of biodeposits from mussel farms: the importance of simulating biodeposit erosion and decay. *Aquaculture* **291**: 168–178.

Giles H, Pilditch CA, Bell DG (2006) Sedimentation from mussel (*Perna canaliculus*) culture in the Firth of Thames, New Zealand: impacts on sediment oxygen and nutrient fluxes. *Aquaculture* **261**: 125–140.

Goulletquer P (2020) *Cultured Aquatic Species Information Programme. Mytilus edulis*. Food and Agriculture Organization of the United Nations (FAO). [Cited 11 Jan 2019.] Available from URL: http://www.fao.org/fishery/culturedspecies/Mytilus_edulis/en.

Grant C, Archambault P, Olivier F, McKindsey CW (2012) Influence of "bouchot" mussel culture on the benthic environment in a dynamic intertidal system. *Aquaculture Environment Interactions* **2**: 117–131.

Grant J, Bacher C (2001) A numerical model of flow modification induced by suspended aquaculture in a Chinese bay. *Canadian Journal of Fisheries and Aquatic Sciences* **58**: 1003–1011.

Grant J, Bacher C, Cranford PJ, Guyondet T, Carreau M (2008) A spatially explicit ecosystem model of seston depletion in dense mussel culture. *Journal of Marine Systems* **73**: 155–168.

Grant J, Pastres R (2019) Ecosystem models of bivalve aquaculture: implications for supporting goods and services. In: Smaal A, Ferreira JG, Grant J, Petersen JK, Strand Ø (eds) *Goods and Services of Marine Bivalves*, pp. 507–526. Springer Open, Switzerland.

Gutiérrez JL, Jones CG, Strayer DL, Iribarne OO (2003) Mollusks as ecosystem engineers: the role of shell production in aquatic habitats. *Oikos* **101**: 79–90.

Haines R, Hattam C, Pantzar M, Russi D (2018) *Study on the Economic Benefits of MPAs and SPMs*. European Commission, Brussels.

Halpern BS, Lester SE, Kellner JB (2009) Spillover from marine reserves and the replenishment of fished stocks. *Environmental Conservation* **36**: 268–276.

Hambrey J, Evans S (2016) Aquaculture in England, Wales and Northern Ireland: an analysis of the economic contribution and value of the major sub-sectors and the most important farmed species. *SEAFISH*.

Hargrave BT, Doucette LI, Cranford PJ, Law BA, Milligan TG (2008) Influence of mussel aquaculture on sediment organic enrichment in a nutrient-rich coastal embayment. *Marine Ecology Progress Series* **365**: 137–149.

Hartstein ND, Rowden AA (2004) Effect of biodeposits from mussel culture on macroinvertebrate assemblages at sites of

different hydrodynamic regime. *Marine Environmental Research* **57**: 339–357.
Hartstein ND, Stevens CL (2005) Deposition beneath long-line mussel farms. *Aquacultural Engineering* **33**: 192–213.
Heery EC, Bishop MJ, Critchley LP, Bugnot AB, Airoldi L, Mayer-Pinto M *et al.* (2017) Identifying the consequences of ocean sprawl for sedimentary habitats. *Journal of Experimental Marine Biology and Ecology* **492**: 31–48.
Hilborn R, Banobi J, Hall SJ, Pucylowski T, Walsworth TE (2018) The environmental cost of animal source foods. *Frontiers in Ecology and the Environment* **16**: 329–335.
Hondolero D, Edwards MS (2017) Changes in ecosystem engineers: the effects of kelp forest type on currents and benthic assemblages in Kachemak Bay, Alaska. *Marine Biology* **164**: 81.
Horta e Costa B, Claudet J, Franco G, Erzini K, Caro A, Gonçalves EJ (2016) A regulation-based classification system for Marine Protected Areas (MPAs). *Marine Policy* **72**: 192–198.
Hulot V, Saulnier D, Lafabrie C, Gaertner-Mazouni N (2018) Shellfish culture: a complex driver of planktonic communities. *Reviews in Aquaculture* **12**: 33–46.
Inger R, Attrill MJ, Bearhop S, Broderick AC, Grecian JW, Hodgson DJ *et al.* (2009) Marine renewable energy: potential benefits to biodiversity? An urgent call for research. *Journal of Applied Ecology* **46**: 1145–1153.
Inglis GJ, Gust N (2003) Potential indirect effects of shellfish culture on the reproductive success of benthic predators. *Journal of Applied Ecology* **40**: 1077–1089.
Jackson GA, Winant CD (1983) Effect of a kelp forest on coastal currents. *Continental Shelf Research* **2**: 75–80.
Jackson JBC, Kirby MX, Berger WH, Bjorndal KA, Botsford LW, Bourque BJ *et al.* (2001) Historical overfishing and the recent collapse of coastal ecosystems. *Science* **293**: 629–637.
Jiang W, Gibbs MT (2005) Predicting the carrying capacity of bivalve shellfish culture using a steady, linear food web model. *Aquaculture* **244**: 171–185.
Kapetsky JM, Aguilar-Manjarrez J, Jenness J (2013) *A Global Assessment of Offshore Mariculture Potential from a Spatial Perspective*. FAO Fisheries and Aquaculture Technical Paper No. 549. FAO, Rome.
Kaspar HF, Gillespie PA, Boyer IC, McKenzie AI (1985) Effects of mussel aquaculture on the nitrogen cycle and benthic communities in Kenepuru Sound, Marlborough Sounds, New Zealand. *Marine Biology* **85**: 127–136.
Keeley N (2013) Benthic effects. In Morrisey D (ed.), *Literature Review of Ecological Effects of Aquaculture*, pp. 3.1–3.33. Ministry for Primary Industries, Cawthron Institute & National Institute for Water and Atmospheric Research Ltd, New Zealand.
Keeley N, Forrest B, Hopkins G, Gillespie P, Knight B, Webb S *et al.* (2009) *Sustainable aquaculture in New Zealand: review of the ecological effects of farming shellfish and other non-finfish species*. Minitry of Fisheries. Cawthron Report No. 1476, pp. 150 plus appendices.
Kingsford MJ (1993) Biotic and abiotic structure in the pelagic environment: importance to small fishes. *Bulletin of Marine Science* **53**: 393–415.
Klinger DH, Maria A, Davíðsdóttir B, Winter A, Watson JR (2018) The mechanics of blue growth: management of oceanic natural resource use with multiple, interacting sectors. *Marine Policy* **87**: 356–362.
Kumar M, Cripps S (2012) Chapter 4: environmental aspects. In: Lucas JS, Southgate PC (eds) *Aquaculture: Farming Aquatic Animals and Plants*, pp. 84–106. John Wiley & Sons Ltd, West Sussex, UK.
La Rosa T, Mirto S, Favaloro E, Savona B, Sarà G, Danovaro R *et al.* (2002) Impact on the water column biogeochemistry of a Mediterranean mussel and fish farm. *Water Research* **36**: 713–721.
Lacoste É, Drouin A, Weise AM, Archambault P, McKindsey CW (2018) Low benthic impact of an offshore mussel farm in Îles-de-la-Madeleine, eastern Canada. *Aquaculture Environment Interactions* **10**: 473–485.
Landmann J, Ongsiek T, Goseberg N, Heasman K, Buck B, Paffenholz J-A *et al.* (2019) Physical modelling of blue mussel dropper lines for the development of surrogates and hydrodynamic coefficients. *Journal of Marine Science and Engineering* **7**: 65.
Lasiak TA, Underwood AJ, Hoskin M (2006) An experimental assessment of the potential impacts of longline mussel farming on the infauna in an open coastal embayment. *Aquatic Conservation: Marine and Freshwater Ecosystems* **16**: 289–300.
Le Gouvello R, Hochart LE, Laffoley D, Simard F, Andrade C, Angel D *et al.* (2017) Aquaculture and marine protected areas: potential opportunities and synergies. *Aquatic Conservation: Marine and Freshwater Ecosystems* **27**: 138–150.
LeBlanc A, Landry T, Miron G (2003) Identification of fouling organisms covering mussel lines and impact of a common defouling method on the abundance of foulers in Tracadie Bay, Prince Edward Island. *Canadian Technical Report of Fisheries and Aquatic Sciences* **2477**: 18.
Lehane C, Davenport J (2002) Ingestion of mesozooplankton by three species of bivalve; *Mytilus edulis*, Cerastoderma edule and Aequipecten opercularis. *Journal of the Marine Biological Association of the United Kingdom* **82**: 615–619.
Lehane C, Davenport J (2006) A 15-month study of zooplankton ingestion by farmed mussels (*Mytilus edulis*) in Bantry Bay, Southwest Ireland. *Estuarine, Coastal and Shelf Science* **67**: 645–652.
Lester SE, Stevens JM, Gentry RR, Kappel CV, Bell TW, Costello CJ *et al.* (2018) Marine spatial planning makes room for offshore aquaculture in crowded coastal waters. *Nature Communications* **9**: 945.
Lin J, Li C, Zhang S (2016) Hydrodynamic effect of a large offshore mussel suspended aquaculture farm. *Aquaculture* **451**: 147–155.
Lovatelli A, Manjarrez J, Soto D (2013) Expanding mariculture farther offshore. Technical, environmental, spatial and

governance challenges. FAO Technical Workshop, 22–25 March 2010.

Lucas JS (2012) Chapter 23 bivalve molluscs. In: Lucas JS, Southgate PC (eds) *Aquaculture: Farming Aquatic Animals and Plants*, pp. 541–566. John Wiley & Sons Ltd, West Sussex, UK.

Maar M, Nielsen TG, Petersen JK (2008) Depletion of plankton in a raft culture of *Mytilus galloprovincialis* in Ría de Vigo, NW Spain. *Aquatic Biology* **4**: 127–141.

Marine Conservation Society (2018) *Good fish guide: mussel, Mytilus edulis (Farmed)*. [Cited 12 March 2019.] Available from URL: https://mcsuk.org/goodfishguide/fish/498.

Matarazzo Suplicy F (2018) A review of the multiple benefits of mussel farming. *Reviews in Aquaculture* **12**: 204–223.

Mckindsey CW, Archambault P, Callier MD, Frédéric O (2011) Influence of suspended and off-bottom mussel culture on the sea bottom and benthic habitats: a review. *Canadian Journal of Zoology* **89**: 622–646.

McKindsey CW, Archambault P, Simard N (2012) Spatial variation of benthic infaunal communities in baie de Gaspé (eastern Canada) – influence of mussel aquaculture. *Aquaculture* **356**: 48–54.

McKindsey CW, Thetmeyer H, Landry T, Silvert W (2006) Review of recent carrying capacity models for bivalve culture and recommendations for research and management. *Aquaculture* **261**: 451–462.

Muñiz O, Revilla M, Rodríguez JG, Laza-Martínez A, Fontán A (2019) Annual cycle of phytoplankton community through the water column: study applied to the implementation of bivalve offshore aquaculture in the southeastern Bay of Biscay. *Oceanologia* **61**: 114–130.

Murray LG, Newell CR, Seed R (2007) Changes in the biodiversity of mussel assemblages induced by two methods of cultivation. *Journal of Shellfish Research* **26**: 153–162.

Nelson PA (2003) Marine fish assemblages associated with fish aggregating devices (FADs): effects of fish removal, FAD size, fouling communities, and prior recruits. *Fishery Bulletin* **101**: 835–850.

Newell CR, Brady DC, Richardson J (2019) Farm-scale production models. In: Smaal JGF, Grant J, Petersen JK, Strand Ø (eds) *Goods and Services of Marine Bivalves*, pp. 485–506. Springer Open, Switzerland.

Newell CR, Richardson J (2014) The effects of ambient and aquaculture structure hydrodynamics on the food supply and demand of mussel rafts. *Journal of Shellfish Research* **33**: 257–272.

Newell RIE (2004) Ecosystem influences of natural and cultivated populations of suspension-feeding bivalve molluscs: a review. *Journal of Shellfish Research* **23**: 51–61.

Nizzoli D, Welsh DT, Bartoli M, Viaroli P (2005) Impacts of mussel (*Mytilus galloprovincialis*) farming on oxygen consumption and nutrient recycling in a eutrophic coastal lagoon. *Hydrobiologia* **550**: 183–198.

Nizzoli D, Welsh DT, Fano EA, Viaroli P (2006) Impact of clam and mussel farming on benthic metabolism and nitrogen cycling, with emphasis on nitrate reduction pathways. *Marine Ecology Progress Series* **315**: 151–165.

O'Donncha F, Hartnett M, Nash S (2013) Physical and numerical investigation of the hydrodynamic implications of aquaculture farms. *Aquacultural Engineering* **52**: 14–26.

O'Donncha F, James SC, Ragnoli E (2016) Modelling study of the effects of suspended aquaculture installations on tidal stream generation in Cobscook Bay. *Renewable Energy* **102**: 65–76.

Pauly D, Christensen V, Guénette S, Pitcher TJ, Sumaila UR, Walters CJ *et al*. (2002) Towards sustainability in world fisheries. *Nature* **418**: 689–695.

Pechlivanidis G, Keramaris E, Savvidis Y (2018) Turbulent simulation of the flow around different positions of mussel shocks. *Proceedings* **2**: 574.

Petersen J (2004) Methods for measurement of bivalve clearance rate-hope for common understanding. *Marine Ecology Progress Series* **276**: 309–310.

Plew DR (2005) PhD Thesis. The hydrodynamic effects of long-line mussel farms.

Plew DR (2011) Depth-averaged drag coefficient for modeling flow through suspended canopies. *Journal of Hydraulic Engineering* **137**: 234–247.

Plew DR (2013) Hydrodynamic effects. In Knight B (ed.), *Literature Review of Ecological Effects of Aquaculture*, pp. 11.1–11.23. Ministry for Primary Industries, Cawthron Institute & National Institute for Water and Atmospheric Research Ltd, New Zealand.

Plew DR, Spigel RH, Stevens CL, Nokes RI, Davidson MJ (2006) Stratified flow interactions with a suspended canopy. *Environmental Fluid Mechanics* **6**: 519–539.

Plew DR, Stevens CL, Spigel RH, Hartstein ND (2005) Hydrodynamic implications of large offshore mussel farms. *IEEE Journal of Oceanic Engineering* **30**: 95–108.

Prins TC, Smaal AC, Dame RF (1997) A review of the feedbacks between bivalve grazing and ecosystem processes. *Aquatic Ecology* **31**: 349–359.

Rampazzo F, Berto D, Giani M, Brigolin D, Covelli S, Cacciatore F *et al*. (2013) Impact of mussel farming on sedimentary geochemical properties of a Northern Adriatic area influenced by freshwater inflows. *Estuarine, Coastal and Shelf Science* **129**: 49–58.

Rees SE, Sheehan EV, Stewart BD, Clark R, Appleby T, Attrill MJ *et al*. (2020) Emerging themes to support ambitious UK marine biodiversity conservation. *Marine Policy* **117**: 103864.

Rosman JH, Denny MW, Zeller RB, Monismith SG, Koseff JR (2013) Interaction of waves and currents with kelp forests (*Macrocystis pyrifera*): Insights from a dynamically scaled laboratory model. *Association for the Sciences of Limnology and Oceanography* **58**: 790–802.

Roycroft D, Kelly TC, Lewis LJ (2007) Behavioural interactions of seabirds with suspended mussel longlines. *Aquaculture International* **15**: 25–36.

Ryan J (2004) Farming the Deep Blue. *Bord Iascaigh Mhara – The Irish Sea Fisheries Board and Irish Marine Institute*. [Cited

11 Jan 2019.] Available from URL: http://www.bim.ie/media/bim/content/downloads/Farming,the,Deep,Blue.pdf.

Sala E, Lubchenco J, Grorud-Colvert K, Novelli C, Roberts C, Sumaila UR (2018) Assessing real progress towards effective ocean protection. *Marine Policy* **91**: 11–13.

Sequeira A, Ferreira JG, Hawkins AJS, Nobre A, Lourenço P (2008) Trade-offs between shellfish aquaculture and benthic biodiversity: a modelling approach for sustainable management. *Aquaculture* **274**: 313–328.

Sheehan EV, Bridger D, Mascorda Cabre L, Cartwright A, Cox D, Rees S *et al.* (2019) *Bivalves Boost Biodiversity*, pp. 18–21. Food, Science and Technology, London, UK.

Shi J, Wei H, Zhao L, Yuan Y, Fang J, Zhang J (2011) A physical-biological coupled aquaculture model for a suspended aquaculture area of China. *Aquaculture* **318**: 412–424.

Singh GG, Cisneros-Montemayor AM, Swartz W, Cheung W, Guy JA, Kenny TA *et al.* (2018) A rapid assessment of co-benefits and trade-offs among sustainable development goals. *Marine Policy* **93**: 223–231.

Smaal AC, Ferreira JG, Grant J, Petersen JK, Strand Ø (2019) *Goods and Services of Marine Bivalves*. Springer Open, Switzerland.

Solandt JL, Mullier T, Elliott S, Sheehan EV (2020) Managing marine protected areas in Europe: moving from 'feature-based' to 'whole-site' management of sites. In Humphreys J, Clark R (eds.), *Marine Protected Areas: Science, Policy and Management*, pp. 157–181. Elsevier, Oxford, UK.

Soto D, Aguilar-Manjarrez J, Brugère C, Angel D, Bailey C, Black K *et al.* (2008) Applying an ecosystem-based approach to aquaculture: principles, scales and some management measures. In Soto D, Aguilar-Manjarrez J, Hishamunda N (Eds.), *Building an Ecosystem Approach to Aquaculture*. FAO/Universitat de les Illes Balears Expert Workshop. 7–11 May 2007, Palma de Mallorca, Spain. FAO Fisheries and Aquaculture Proceedings. No. 14, pp. 15–35. Rome, Italy.

Spencer BE (2002) *Molluscan Shellfish Farming*. Fishing News Books, a Division of Blackwell Publishing, Malden, MA.

STECF (2018) *Scientific, Technical and Economic Committee for Fisheries – Economic report of the EU aquaculture sector (STECF-18-19)*. Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-79402-5. [Cited 11 Jan 2019.] Available from URL: https://op.europa.eu/en/publication-detail/-/publication/7f9c98f0-0fe4-11e9-81b4-01aa75ed71a1.

Stelzenmüller V, Schulze T, Gimpel A, Bartelings H, Bello E, Bergh O *et al.* (2013) Guidance on a better integration of aquaculture, fisheries, and other activities in the coastal zone: from tools to practical examples. *COEXIST project*.

Stenton-Dozey J (2013) Pelagic effects. In Paul Gillespie W, Cawthron Institute, Nelson Philip Heath, NIWA (eds), *Litrature Review of Ecological Effects of Aquaculture*, pp. 1–21. Ministry for Primary Industries, Cawthron Institute & National Institute for Water and Atmospheric Research Ltd, New Zealand.

Stenton-Dozey JME, Jackson LF, Busby AJ (1999) Impact of mussel culture on macrobenthic community structure. *Marine Pollution Bulletin* **39**: 357–366.

Stenton-Dozey J, Probyn T, Busby A (2001) Impact of mussel (*Mytilus galloprovincialis*) raft-culture on benthic macrofauna, *in situ* oxygen uptake, and nutrient fluxes in Saldanha Bay, South Africa. *Canadian Journal of Fisheries and Aquatic Sciences* **58**: 1–11.

Stevens CL, Petersen JK (2011) Turbulent, stratified flow through a suspended shellfish canopy: implications for mussel farm design. *Aquaculture Environment Interactions* **2**: 87–104.

Stevens CL, Plew DR, Smith MJ, Fredriksson DW (2007) Hydrodynamic forcing of long-line mussel farms: observations. *Journal of Waterway, Port, Coastal, and Ocean Engineering* **133**: 192–199.

Stevens C, Plew D, Hartstein N, Fredriksson D (2008) The physics of open-water shellfish aquaculture. *Aquacultural Engineering* **38**: 145–160.

Strand Ø, Bergh Ø, Pastres R, Icely J, Galparsoro I, Éva K *et al.* (2017) Ecosystem approach to making space for aquaculture. EU Horizon 2020 project grant no. 633476. Aquaspace.

Strohmeier T, Aure J, Duinker A, Castberg T, Svardal A, Strand Ø (2005) Flow reduction, seston depletion, meat content and distribution of diarrhetic shellfish toxins in a long-line Blue mussel (*Mytilus edulis*) farm. *Journal of Shellfish Research* **24**: 15–23.

Strohmeier T, Duinker A, Strand Ø, Aure J (2008) Temporal and spatial variation in food availability and meat ratio in a longline mussel farm (*Mytilus edulis*). *Aquaculture* **276**: 83–90.

Strohmeier T, Strand Ø, Alunno-Bruscia M, Duinker A, Cranford PJ (2012) Variability in particle retention efficiency by the mussel *Mytilus edulis*. *Journal of Experimental Marine Biology and Ecology* **412**: 96–102.

Troell M, Joyce A, Chopin T, Neori A, Buschmann AH, Fang JG (2009) Ecological engineering in aquaculture - potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems. *Aquaculture* **297**: 1–9.

Trottet A, Roy S, Tamigneaux E, Lovejoy C, Tremblay R (2008) Influence of suspended mussel farming on planktonic communities in Grande-Entrée Lagoon, Magdalen Islands (Québec, Canada). *Aquaculture* **276**: 91–102.

Tseung HL, Kikkert GA, Plew DR (2016) Hydrodynamics of suspended canopies with limited length and width. *Environmental Fluid Mechanics* **16**: 145–166.

Tyler-Walters H (2008) *Mytilus edulis common mussel*. [Cited 29 January 2019.] Available from URL: https://www.marlin.ac.uk/species/detail/1421.

Underwood AJ (1990) Experiments in ecology and management: their logics, functions and interpretations. *Australian Journal of Ecology* **15**: 365–389.

United Nations (2015) *Transforming our world: the 2030 Agenda for sustainable development*. UN Sustainable Development Goals. [Cited 23 Oct 2019.] Available from URL: https://sustainabledevelopment.un.org/post2015/transformingourworld/publication.

Upton HF, Buck EH (2010) Open ocean aquaculture. In: *CRS Report to Congress 7-5700: Congressional Research Service, Washington DC*, pp. 1–21.

Weise AM, Cromey CJ, Callier MD, Archambault P, Chamberlain J, McKindsey CW (2009) Shellfish-DEPOMOD: modelling the biodeposition from suspended shellfish aquaculture and assessing benthic effects. *Aquaculture* **288**: 239–253.

Weitzman J (2019) Applying the ecosystem services concept to aquaculture: a review of approaches, definitions, and uses. *Ecosystem Services* **35**: 194–206.

Wilding TA, Nickell TD (2013) Changes in benthos associated with mussel (*Mytilus edulis* L.) farms on the west-coast of Scotland. *PLoS One* **8**: e68313.

Ysebaert T, Hart M, Herman PMJ (2009) Impacts of bottom and suspended cultures of mussels *Mytilus* sp. on the surrounding sedimentary environment and macrobenthic biodiversity. *Helgoland Marine Research* **63**: 59–74.

Zu Ermgassen PSE, Thurstan RH, Corrales J, Alleway H, Carranza A, Dankers N *et al.* (2020) The benefits of bivalve reef restoration: a global synthesis of underrepresented species. *Aquatic Conservation: Marine and Freshwater Ecosystems* **30**: 2050–2065.

Zupan M, Fragkopoulou E, Claudet J, Erzini K, Horta e Costa B, Gonçalves EJ (2018) Marine partially protected areas: drivers of ecological effectiveness. *Frontiers in Ecology and the Environment* **16**: 1–7.