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

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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).

Keywords: Aquaculture, Blue Growth, Ecology, MPAs, 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 (Galparsoro *et al.* 2020; Jackson *et al.* 2001; Pauly *et al.* 2002) 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 fin-fish, shellfish, and seaweed (Duarte *et al.* 2009; Landmann *et al.* 2019; Strand *et al.* 2017).

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 (Callier *et al.* 2017; Galparsoro *et al.* 2020; Lacoste *et al.* 2018; Landmann *et al.* 2019; Lester *et al.* 2018; Stelzenmüller *et al.* 2013; Strand *et al.* 2017).

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) (FAO 2016; Lucas 2012; 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 (Landmann *et al.* 2019; Strand *et al.* 2017; Tyler-Walters 2008).

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).

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

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 120-150m, each longline consists of two parallel "backbone" ropes supported by buoys at regular intervals keeping the structure afloat and moorings anchored to the seabed (Figure 1 c-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 5-30 m depending on water depth and nutrient availability (Landmann *et al.* 2019; Stevens *et al.* 2008). In areas with strong currents, waves and winds, longline farms have been submerged 5-10m using buoyancy controls or altering the mooring design (Figure 1 d) allowing mussels to grow faster and have higher meat/shell ratios, making them a preferred method and becoming the dominant technique used (Brenner *et al.* 2009; Buck 2007; Gagnon & Bergeron 2017; Kapetsky *et al.* 2013; Stevens *et al.* 2008).

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 (Giles *et al.* 2009; Hilborn *et al.* 2018; Keeley *et al.* 2009; Rampazzo *et al.* 2013). Inshore mussel farms located in low energy environments with a mild hydrodynamic regime are considered to have localised effects (Callier *et al.* 2006; Chamberlain *et al.* 2001; Giles *et al.* 2009; Hartstein & Stevens 2005). 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; Hilborn *et al.* 2018; Keeley *et al.* 2009; Rampazzo *et al.* 2013).

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; Gallardi 2014; Kumar & Cripps 2012; Matarazzo Suplicy 2018; Newell *et al.* 2019) having a positive contribution to the surrounding ecology due to their sediment stabilization 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, pseudo-faeces and marine litter are accumulated beneath and around the farm, affecting the benthic community structure below (Callier *et al.* 2006; Chamberlain *et al.* 2001; Fabi *et al.* 2009; Hartstein & Stevens 2005; Keeley *et al.* 2009; Kumar & Cripps 2012; Mckindsey *et al.* 2011; 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 (Cranford *et al.* 2009; Grant & Bacher 2001; Matarazzo Suplicy 2018; Stevens & Petersen 2011; Strohmeier *et al.* 2005, 2008). 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 (Callier *et al.* 2009; Chamberlain *et al.* 2001; Danovaro *et al.* 2004; Fabi *et al.* 2009; Grant *et al.* 2012; Hartstein & Stevens 2005; Keeley *et al.* 2009; Matarazzo Suplicy 2018; Newell 2004; Rampazzo *et al.* 2013). Raising concerns about the increasing range of aquaculture-environment interactions of intensive bivalve aquaculture (Gallardi 2014; Kumar & Cripps 2012; 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 (D'Amours *et al.* 2008; Inglis & Gust 2003). Studies have reported diverse assemblages of fishes, 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 (Bendell 2014; Chamberlain *et al.* 2001; Gallardi 2014; Mckindsey *et al.* 2011).

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; Kumar & Cripps 2012; Mckindsey *et al.* 2011); while some report negative impacts (Chamberlain *et al.* 2001; Cranford *et al.* 2009; Hargrave *et al.* 2008; Kaspar *et al.* 1985; Keeley 2013; Nizzoli *et al.* 2005, 2006; Stenton-Dozey *et al.* 1999 2001) others result in little or no ecological change relative to surrounding habitats (Crawford *et al.* 2003; D'Amours *et al.* 2008; Danovaro *et al.* 2004; Dimitriou *et al.* 2015; Inglis & Gust 2003; Lasiak *et al.* 2006; McKindsey *et al.* 2012; Wilding & Nickell 2013; Ysebaert *et al.* 2009).

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 (Brenner *et al.* 2009; Buck *et al.* 2018; Fairbanks 2016; Gagnon & Bergeron 2017; Gallardi 2014; Gentry *et al.* 2016 2017; Gibbs 2004; Kapetsky *et al.* 2013; Keeley *et al.* 2009; Lacoste *et al.* 2018; Landmann *et al.* 2019; Muñiz *et al.* 2019; O'Donncha *et al.* 2016; Plew *et al.* 2005; Stevens *et al.* 2007, 2008). 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 (Brenner *et al.* 2009; Buck *et al.* 2005; Kapetsky *et al.* 2013; Lucas 2012; Stevens *et al.* 2007, 2008). 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 1km 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 (Buck *et al.* 2018; Froehlich *et al.* 2017b; Kapetsky *et al.* 2013; Lovatelli *et al.* 2013; Plew *et al.* 2005; Ryan, 2004; Stevens *et al.* 2008; Troell *et al.* 2009).

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; Lacoste *et al.* 2018; Lin *et al.* 2016). Although the significant volumes of organic loading produced by mussel farms have the potential to be dissipated, offsetting the effects seen beneath inshore developments (Lacoste *et al.* 2018; Lin *et al.* 2016), 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 (Figure 2) (Fabi *et al.* 2009; Lacoste *et al.* 2018; Lin *et al.* 2016; Rampazzo *et al.* 2013).

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 (Buck *et al.* 2018; Galparsoro *et al.* 2020; Lacoste *et al.* 2018; Stevens *et al.* 2008), licensing intricacies and lack of clear policy and management, social perceptions and political obstacles (Fairbanks 2016; Galparsoro *et al.* 2020; Kapetsky *et al.* 2013; Upton & Buck 2013). 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 (Froehlich *et al.* 2017a; Mckindsey *et al.* 2011; Upton & Buck 2013).

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 (Callier *et al.* 2017; Fabi *et al.* 2009; Galparsoro *et al.* 2020; Lacoste *et al.* 2018; Landmann *et al.* 2019; Lester *et al.* 2018; Lin *et al.* 2016; Stelzenmüller *et al.* 2013; Strand *et al.* 2017; Tseung *et al.* 2016; Upton & Buck 2013), 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 stablish 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 were 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 regards 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 (O'Donncha *et al.* 2013; Plew *et al.* 2006) by creating velocity shears and mixing layers and producing small scale turbulence causing enhanced dispersion (Figure 3) (Matarazzo Suplicy 2018; O'Donncha *et al.* 2013, 2016; Plew 2013; Plew *et al.* 2005, 2006), 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; Fabi *et al.* 2009; Plew 2013; Plew *et al.* 2005, 2006; 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 (Figure 2 and Figure 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 2013; Plew *et al.* 2005, 2006; Stevens *et al.* 2008; Strohmeier *et al.* 2005) 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; Lin *et al.* 2016; O'Donncha *et al.* 2013; Plew 2013). 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; Lin *et al.* 2016; Pechlivanidis *et al.* 2018; Stenton-Dozey 2013).

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 (Hondolero & Edwards 2017; Jackson & Winant 1983; Plew *et al.* 2005, 2006; Rosman *et al.* 2013). 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 meters 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 (Alleway *et al.* 2019; Chen *et al.* 2019; Mckindsey *et al.* 2011; Plew *et al.* 2005, 2006).

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 (Figure 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 (Figure 3) (Plew 2013; Plew *et al.* 2006).

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 (Lin *et al.* 2016; Plew *et al.* 2005; Rampazzo *et al.* 2013). 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 (Hulot *et al.* 2018; Lin *et al.* 2016; Plew 2013). 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 (Delaux *et al.* 2011; Plew *et al.* 2006). 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 (Delaux *et al.* 2011; Plew 2005; Smaal *et al.* 2019; Stevens *et al.* 2008). 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 of 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 2013, 2011). A study of New Zealand mussel longline farms has shown that beneath the farm velocities are off-set by around the farm horizontal water flow diversion producing an increase of seabed shear stress of up to 20% (Plew 2013, 2011).

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 2011; Plew *et al.* 2006). 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 of 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 (Tseung *et al.* 2016; Plew *et al.* 2005, 2006). 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) (Figure 2 and Figure 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).

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 (Delaux *et al.* 2011; Plew *et al.* 2005). 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.

Stratification distortion and particle residence time

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 (Plew 2013; Stevens *et al.* 2008). 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 to 20% within its footprint (O'Donncha *et al.* 2016), reducing food renewal flows and accumulating biodeposits within the structure by altering sedimentation rates (Lin *et al.* 2016; O'Donncha *et al.* 2016; Stevens *et al.* 2007, 2008) 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 2013; Plew *et al.* 2005, 2006). 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 (Plew 2013; Stevens *et al.* 2008).

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 (Figure 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; Mckindsey *et al.* 2011; Spencer 2002). 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 (Mckindsey *et al.* 2011; Newell 2004). 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.* 2009, 2006; 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 of biodeposits underneath the structure has been observed in certain developments, studies have found that physical and chemical changes reduce to natural levels approximately 30 to 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 of 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 to 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 (Callier *et al.* 2008; Chamberlain *et al.* 2001; Lacoste *et al.* 2018; Ysebaert *et al.* 2009).

Mobile macrofauna interactions

Mobile benthic fauna, including fish and crustaceans, can be affected by mussel aquaculture operations. The main mechanisms are: (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 (Callier *et al.* 2017; Keeley 2013; Mckindsey *et al.* 2011) 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 (Figure 6 and Figure 7) (Callier *et al.* 2017; Inglis & Gust 2003; Mckindsey *et al.* 2011). 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 windfarms), enhancing mobile macrofauna communities, operating as reefs (Callier *et al.* 2017; Heery *et al.* 2017; Inger *et al.* 2009). 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 (Callier *et al.* 2017; Mckindsey *et al.* 2011). 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 (Figure 2) (Callier *et al.* 2017; Inglis & Gust 2003; Lacoste *et al.* 2018; Mckindsey *et al.* 2011). As hard-bottom communities often are more diverse and have greater biomass and higher productivity than soft-bottom ones, this 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 (Cranford *et al.* 2008; Froján *et al.* 2018; La Rosa *et al.* 2002; Trottet *et al.* 2008), recent attention has been given to farms attracting pelagic fish and vagile macroinvertebrates as well as interacting with planktonic communities (Figure 4 and Figure 5). Additionally, organisms growing among mussel longlines and other farm structures such as algae and invertebrate organisms (epifauna) may also attract such organisms (Callier *et al.* 2017; Mckindsey *et al.* 2011).

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 (FADs)

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 (Figure 2 and Figure 4-6) (Callier *et al.* 2017; Cornelisen 2013). Floating structures occurring in the open ocean are known to attract pelagic fish, widely recognised to act as FADs (Kingsford 1993; Matarazzo Suplicy 2018; Nelson 2003). As many studies have found that wild fish are attracted to aquaculture developments (Callier *et al.* 2017; Cornelisen 2013), farms are being thought to be acting as FADs due to the physical structure (Carpenter *et al.* 2009; Clavelle *et al.* 2018; Keeley *et al.* 2009) 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 (Clavelle *et al.* 2018; Gutiérrez *et al.* 2003). Consequently, providing a direct food source for other predators, making farms attractive to higher food-web organisms such as pelagic fishes and other vagile organisms (Callier *et al.* 2017; Mckindsey *et al.* 2011).

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 (Brehmer *et al.* 2003; Gerlotto *et al.* 2001; 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 (Clement 2013; Keeley *et al.* 2009; Roycroft *et al.* 2007). 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 (Clement 2013; Roycroft *et al.* 2007). 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 (Callier *et al.* 2017; Gentry *et al.* 2016; Keeley *et al.* 2009; 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 (Grant & Pastres 2019; Hulot *et al.* 2018; Lehane & Davenport 2002, 2006; Petersen 2004; Prins *et al.* 1997). 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 pseudo-faeces, primary production is stimulated, shifting the system towards a dominance of smaller planktonic species within the water column of the aquaculture development (Hulot *et al.* 2018; Strohmeier *et al.* 2012). 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 (Figure 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 (Fairbanks 2016; Keeley *et al.* 2009; Upton & Buck 2013). 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 (Clavelle *et al.* 2018; Keeley *et al.* 2009). 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 (Clavelle *et al.* 2018; Halpern *et al.* 2009; Sheehan *et al.* 2019). In terms of conservation, this has been seen to be serving as a *de facto* marine protected areas (MPAs) (Clavelle *et al.* 2018; Halpern *et al.* 2009; 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 (European Commission 2019; Le Gouvello *et al.* 2017; Sala *et al.* 2018). 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; Duarte *et al.* 2020; Le Gouvello *et al.* 2017; Sala *et al.* 2018; United Nations 2015), the Blue Economy and in particular aquaculture as the fastest growing food industry in the world, must move forward together (Blanchard *et al.* 2017; Ferreira *et al.* 2009; 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 (Claudet *et al.* 2020; Edgar *et al.* 2014; Galparsoro *et al.* 2020; Rees *et al.* 2020; Sala *et al.* 2018). 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 (European Commission 2019; Sala *et al.* 2018).

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 (Rees *et al.* 2020; Sala *et al.* 2018).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 (FAO 2018; Soto *et al.* 2008) to be at the forefront of Blue Growth goals in conservation aquaculture for the planning, development and management of the industry (European Commission 2019; FAO 2018; Froehlich *et al.* 2017a; Klinger *et al.* 2018) 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 minimizing 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 licencing procedures, lack of clear policy and management, space constrains and environmental and economic factors (European Commission 2019; Fairbanks 2016; Galparsoro *et al.* 2020; Kapetsky *et al.* 2013; Matarazzo Suplicy 2018). 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 (European Commission 2019; Galparsoro *et al.* 2020; Matarazzo Suplicy 2018).

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 (Callier *et al.* 2017; Mckindsey *et al.* 2011; Underwood 1990; Upton & Buck 2013).

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 (European Commission 2019; FAO 2018; Froehlich *et al.* 2017a; Hambrey & Evans 2016; Klinger *et al.* 2018; Smaal *et al.* 2019; Soto *et al.* 2008; Upton & Buck 2013).

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 (Chen *et al.* 2019; Gagnon & Bergeron 2017; Newell & Richardson 2014; O'Donncha *et al.* 2013, 2016; Plew 2011; Plew *et al.* 2005; Stevens & Petersen 2011). 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 (Lin *et al.* 2016; Stevens & Petersen 2011).

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 (Lin *et al.* 2016; Plew *et al.* 2005; Stevens & Petersen 2011) and overall ecosystem services capacity of the farm helping estimate consequent ecological impacts (Chen *et al.* 2019; Plew 2013; Stevens *et al.* 2008) and the farm's footprint (Tseung *et al.* 2016, Plew *et al.* 2005, 2006) in order to provide factual and effective MSP (FAO 2018; Klinger *et al.* 2018; Landmann *et al.* 2019; Mckindsey *et al.* 2011; Plew 2013).

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 (Callier *et al.* 2009; Cranford *et al.* 2009; Hartstein & Stevens 2005; Lovatelli *et al.* 2013; McKindsey *et al.* 2006; Stevens *et al.* 2008) 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; Lacoste *et al.* 2018; Mckindsey *et al.* 2011).

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 (Giles *et al.* 2009; Hartstein & Rowden 2004; Hartstein & Stevens 2005; Lacoste *et al.* 2018; Lin *et al.* 2016). 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; Lacoste *et al.* 2018; Lin *et al.* 2016).

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; Lacoste *et al.* 2018; Mckindsey *et al.* 2011). 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 (Callier *et al.* 2017; Inglis & Gust 2003; Mckindsey *et al.* 2011) 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 (Callier *et al.* 2017; Keeley *et al.* 2009; Mckindsey *et al.* 2011). 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 (Hulot *et al.* 2018; Lehane & Davenport 2002) 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, specially due to seasonal variations (Hulot *et al.* 2018; Strohmeier *et* *al.* 2008) 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 (Alleway *et al.* 2019; Froehlich *et al.* 2017a; Le Gouvello *et al.* 2017; 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 stablish positive and negative synergies (Froehlich *et al.* 2017a; Le Gouvello *et al.* 2017) having at its core an integrated ecosystem-based approach (Rees *et al.* 2020; Sala *et al.* 2018).

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 (Clavelle *et al.* 2018; FAO 2018; Froehlich *et al.* 2017a; Le Gouvello *et al.* 2017; 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 (Duarte *et al.* 2020; Edgar *et al.* 2014; Solandt *et al.* 2020; Zupan *et al.* 2018). 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 (Callier *et al.* 2017; Galparsoro *et al.* 2020; Kapetsky *et al.* 2013; Lacoste *et al.* 2018; Landmann *et al.* 2019; Lester *et al.* 2018; Stelzenmüller *et al.* 2013; Strand *et al.* 2017) 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.

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Tables

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

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

Figure Legends

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).

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)

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, adapted from Plew *et al.* 2005).

Figure 4 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 6m depth. Longline ropes are full of mussels and biofouling (Mascorda Cabre 2020).

Figure 5 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 6m depth. Longline ropes are full of mussels and biofouling (Mascorda Cabre 2019).

Figure 6 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 7 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).