POTENTIAL AQUACULTURE PRODUCTION AT OFFSHORE RENEWABLE ENERGY SITES

by

MORGAN LORD

JULY 2020

Commented [KM1]: The authors are very grateful to one of Michel Kaiser's former Masters students at Heriot-Watt University – Morgan Lord - who has given us permission to share her dissertation thesis as a model of good practice.

This thesis was awarded a 'distinction' mark during the recent Covid-19 pandemic. A distinction in the UK system has a range of marks from 70-100. Students scoring 70 or over are considered to be in the top 5% of their cohort.

Due to Covid pandemic, the student had to abandon their original thesis idea and develop a 'desk' based project. The thesis demonstrates what can be achieved by using information gathered from internet and open access public resources.

When using this text and gauging it against your own education system expectations, it is important to understand that a UK model Masters course is comprised of 9 months of taught courses and 3 months of pure research resulting in a dissertation. In contrast, a U.S. model Masters course is comprised of taught courses in the first year with a prolonged period of research lasting up to 18 months that results in a dissertation. The example dissertation here is the result of 3 months of research and write up. It is not unusual for MSc theses to be published in peer reviewed journals at some point and a good supervisor will encourage excellent students to pursue this opportunity.

We use the comments tool to highlight elements of the thesis that stand out as good practice. I also flag some of the areas where some elements could have been improved.

Some sections of text have been removed for brevity and to prevent plagiarism. Removed text is highlighted in red.

There are 38 comments alongside the text.

Contents

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Acknowledgements

First and foremost, thanks must be given ….. Thanks are also extended to xxxxxx of yyyyyyyyyy and wwwwwwwww, nnnnnnnnn Ltd, for sharing their expert knowledge and experience of the offshore mussel sector.

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Abstract

Historically, coastal and near-shore areas have been heavily exploited, which has resulted in marine sectors moving developments further offshore. Marine space usage continues to grow and is backed by incentives to boost the blue economy. Co-locating offshore sectors has the potential to make using the offshore environment more sustainable. Co-location involves an offshore site housing two or more blue economy sectors within the same site – such as offshore wind and aquaculture. Offshore wind is already a well-developed industry within Scotland, with Crown Estate Scotland estimating investment in Scottish offshore windfarms could surpass £8bn. Aquaculture is also a well-developed sector within Scotland, contributing over £1.8 billion to the Scottish economy. However, aquaculture in Scotland currently takes places mainly within coastal areas and sea lochs with little room for expansion. The feasibility of offshore co-location of wind and aquaculture in Scottish waters has been evaluated through investigating current offshore aquaculture and co-location developments and consideration of potential aquaculture species based on environmental parameters and associated risks. This information was then used to examine nine study sites around Scotland and the potential productivity of mussel farms at these sites to establish if there was an area best suited to offshore co-location.

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1. Introduction

In 2012 the European Commission launched its Blue Growth' strategy to support long-term sustainable growth in the marine and maritime sector. The European Commission's push for sustainable growth focuses on five main sectors that are thought to have the greatest potential for innovation and job creation: energy, aquaculture, tourism, biotechnology and marine mineral resources (European Commission, 2017). The European Commission reports that in 2018 the blue economy sector turned over €750 billion and employed ~ 5 million people. To continue to grow sustainably and plan for the continuation of growth it has been suggested that future developments should be utilised by more than one blue economy sector (European Commission, 2020a). As maritime activity increases so does competition for space in the marine environment. Coastal areas are already overexploited. To promote sustainable use of the offshore environment and avoid overexploitation the EU has promoted the development of multi-use offshore platforms (MUPs) (Dalton *et al.*, 2019).

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1.1. Blue Growth in Scotland

Crown Estate Scotland has committed to investing £70 million over the next three years to support the expansion of Scotland's blue economy with a focus on marine and coastal development. It aims to revive coastal communities, renewable energy and sustainable food production. Scotland has a pre-existing offshore wind sector and currently has six operational offshore wind farms (Scottish Natural Heritage, 2020). Scotland aims to achieve net-zero emissions by 2045, which requires a large-scale increase in renewable electricity generation. To achieve this, Crown Estate Scotland has published a list of actions it will take to boost the offshore renewable energy sector including investment in measures to remove sector-wide barriers to further offshore wind investments and enabling access to the seabed for new offshore wind developments (Crown Estate Scotland, 2020). Marine Scotland is responsible for regulating the offshore wind sector in Scottish Seas. Currently, Marine Scotland is in the process of consulting on a sectoral plan for the future development of offshore wind farms (Scottish Natural Heritage, 2020).

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1.2. Renewable Energy

As the global population continues to increase so does the demand for resources (Papandroulakis *et al.*, 2017). Historically, ocean usage mainly consisted of the exploitation of living resources and transportation. More recently, the oceans have been used to supply energy via the oil & gas sector. Presently there is a policy agenda to reduce and move away from traditional energy sources and an increase in renewable energy developments (Young, 2015). The rising population along with increasing concerns about climate change, the negative health effects of air pollution and energy security and access has led to an increased interest in renewable energy technologies (Rodríguez-Rodríguez *et al.*, 2016).

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The capability of renewable technology to produce energy is predicted to increase by 50% between 2019 and 2024 (IEA, 2019b). The production and consumption of renewable energy in the UK has been steadily increasing since 2000. This rise has been largely driven by both national and international incentives to reduce consumption of fossil fuels and decarbonise the energy sector to reduce carbon emissions (IRENA, 2019). The UK boasts a diverse range of renewable energy technologies with wind, solar, photovoltaics, hydro and shoreline wave and tidal contributing to electricity generation alone. The Climate Change Act (2008) saw the UK enter a long-term legally binding target to reduce greenhouse gas emission by 80% relative to 1990 levels by 2050 (UK Government, 2019). To achieve this the UK government has set several goals including achieving 50% of electricity generated to come from renewable sources by 2030 (National Infrastructure Commission, 2019). Renewable energy sources accounted for 33% of the electricity generated in the UK in 2018 (Department for Business Energy and Industrial Strategy, 2019). Wind generation accounts for the largest proportion of renewable electricity generated and accounted for 51.8% of renewable electricity generated in 2018, of which 24.3% was offshore (Department for Business Energy and Industrial Strategy, 2019).

1.3. Offshore wind

Wind power has been a global front runner in terms of total installed capacity with more than half a terawatt of wind generation potential installed globally as of 2018 (IRENA, 2019). The global offshore wind market increased by almost 30% per year between 2010 and 2018 as a result of rapidly improving technology and the deployment of around 150 new offshore wind projects (IEA, 2019a). Currently, most offshore wind farms are in European waters. The majority of offshore wind farms are on monopile foundations in water depths of up to 30m (Lombardi, Bhattacharya and Nikitas, 2017), however as technology advances wind farms are being constructed in increasingly deeper waters (Marine Scotland, 2018).

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1.4. Aquaculture

Aquaculture is the process of cultivating aquatic organisms usually for human consumption. The growing demand for resources teamed with the overexploitation of wild fish stocks has resulted in the aquaculture sector being the fastest growing food production sector globally growing at an average rate of 6.9% per annum (Troell *et al.*, 2009). Seafood comprises one-sixth of animal-sourced food worldwide, and aquaculture is the source of 50% of fish consumed (Golden *et al.*, 2017). Currently, aquaculture takes place mainly in land-based and near-shore sites (Chu *et al.*, 2020). As with the renewables sectors, fragile coastal sites are becoming over-exploited and land-based sites are becoming increasingly competitive and expensive. Despite the growth in the aquaculture sector, demand is expected to be greater than supply by 2030 (Holm, Buck and Langan, 2017). The increased demand and reduced space have resulted in the sector looking to move into deeper offshore waters (Troell *et al.*, 2009).

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Moving aquaculture offshore can offer greater space for continued growth as well as a less fragile and overexploited environment with a greater carrying capacity compared to coastal sites (Holm, Buck and Langan, 2017). In recent years aquaculture technology has been developed with the offshore environment in mind as many predict offshore aquaculture as the future of the sector (California Environmental Associates, 2018). Despite being a seemingly attractive opportunity for growth, offshore aquaculture developments are limited. There are greater risks involved with offshore developments due to the harsh environmental conditions that do not apply to on-land and coastal sites. As with renewables, construction and operation of offshore developments is more costly than closer to land developments and requires considerable capital investment to establish such sites. Concerns regarding the effect of offshore aquaculture both on the environment and on other sea users may also be slowing progress in developments in offshore aquaculture (Lester *et al.*, 2018).

1.5. Multi-Use Platforms (MUPs)

To ensure the marine environment is used in a sustainable way the European Union (EU) introduced the Marine Strategy Framework Directive (MSFD) (2008) and the Maritime Spatial Planning (MSP) Strategy (Dalton *et al.*, 2019). The MSFD states that EU marine waters must achieve Good Environmental Status by 2020. The Directive includes legislation requiring EU members to use the ecosystem approach for managing human activities in the marine environment to integrate the concepts of environmental protection and sustainable use (European Commission, 2020c).

Two pages of text were removed hereafter until section 2.

2. Aims & Thesis Structure

The aims were as follows:

Aim 1: Evaluate current offshore aquaculture and co-location technology

- Thesis starts with a literature review of current offshore aquaculture sites and co-location projects to evaluate current offshore technology and infrastructure.

Aim 2: Evaluate potential candidate species for offshore cultivation in Scottish waters.

- While there are many marine species currently cultivated, there is a shortlist of species with potential for cultivation in Scottish waters based on environmental parameters and associated risks.

Aim 3: Examine the environmental conditions of 9 study sites around mainland Scotland.

- 9 study sites were identified around mainland Scotland based on Crown Estate Scotland's phase 4 round of leasing. Sites were picked to cover the range of environmental conditions around Scotland. Environmental data was collected and integrated for each of the 9 sites.

Aim 4: Model mussel farm productivity at the 9 study sites

- An initial evaluation of the potential productivity of the 9 study sites.

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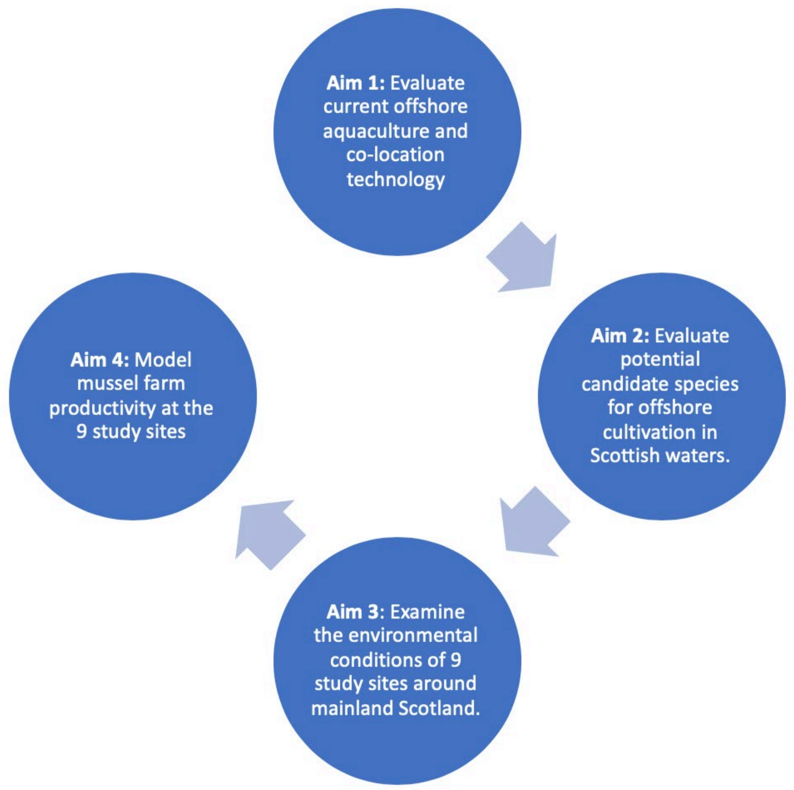

Figure 1: Aims & structure of thesis.

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3. Overview of current technology

Interest in moving aquaculture offshore is increasing as the marine aquaculture sector continues to grow (Troell *et al.*, 2009). Tried and tested equipment and techniques used in near-shore sites are often unsuitable for use at offshore sites where the conditions can be logistically challenging. This has led to offshore aquaculture becoming an innovative and fast-growing research field producing many recent creative solutions to overcome offshore conditions (Buck *et al.*, 2018). Species such as finfish that require regular husbandry (e.g. feeding) come with added issues such as regular husbandry (Bernt and Strømsem, 2016) as the offshore environment can be unpredictable, dangerous and inaccessible. Extreme weather results in offshore wind turbines being inaccessible for 7.7 days per month (Catapults, 2020).

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There is much debate about the pros and cons of moving aquaculture offshore. The deeper waters of the offshore environment increase installation and maintenance costs for anchoring and mooring systems that hold offshore structures in place. Pre-construction surveying of the seabed in deeper waters also comes at an inflated cost compared to shallower coastal sites (Chu *et al.*, 2020). However, moving aquaculture offshore can be beneficial when farming species that introduce uneaten food and faecal matter in the environment as the increased depth can reduce the accumulation of waste in the sediment below cages (Figure 2)(Cardia and Lovatelli, 2015). Deeper offshore waters can provide aquaculture sites with better water quality compared to nearshore sites which often accumulates products of anthropogenic pollution (ICES, 2011). The increased depth and flow can also allow for larger cages with more space for the fish which improves welfare and reduces the probability of disease outbreaks in finfish (Kirchhoff, Rough and Nowak, 2011; Gentry *et al.*, 2017). The increase in space also means structures that sit below the surface of the water can be utilised which can reduce conflicts with other sectors such as shipping (ICES, 2011).

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Figure 2: Effect of depth on waste dispersal beneath cage (Cardia and Lovatelli, 2015).

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The high current speeds of the offshore environment also efficiently disperse waste. Faster moving water can also carry oxygen and food (e.g. chlorophyll a) into the area to replace resources depleted by the cultivated species and reduce biofouling in macroalgae (Rolin *et al.*, 2017). High current speeds can also be problematic. In terms of finfish aquaculture, high currents can result in high energy expenditure from constantly swimming against a strong current. It can also cause food to be wasted if the current expels food from the cage before the fish can eat it.

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3.1. Offshore macroalgae cultivation

Macroalgae is cultivated in around 50 countries worldwide, with China, Indonesia and Japan being the top three produces in value. Consumption of macroalgae has been documented for thousands of years in Asia (Edwards and Watson, 2011). More recently, it is being widely cultivated to meet high demands from the hydrocolloid industry (Ferdouse *et al.*, 2018). Despite being a well-developed industry in Asia, North America and Europe are yet to establish a large-scale market for macroalgae, although interests in the utilisation of macroalgae as a human food source, agricultural animal feed, cosmetics, bioactive components and biofuel is on the rise (Bak, Mols-Mortensen and Gregersen, 2018).

Macroalgae is currently cultivated on basic suspended rope/textile set-ups (Figure 3) and causes little harm to the environment both in terms of waste build up on the seabed and depleting the area of resources. Macroalgae cultivation is promoted in developing countries as a sustainable activity that requires low capital investment and can be an economically viable alternative to fishing. (Ferdouse *et al.*, 2018).

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Figure 3: Suspended rope for macroalgae cultivation suitable for use at wave-exposed sites with depths of >50m.

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3.2. Offshore finfish aquaculture

Finfish farms are usually a series of one or more groups of cages. Cages are structures that usually consist of a floating collar at the surface of the sea with a large net suspended in the water to contain the fish. The floating collars are normally 90-110 meters in circumference with the nets creating an enclosure of 10,000 – 10,000 m^3. The nets contain the fish while allowing water to flow past which brings fresh oxygen and carries away waste products such as faeces, carbon dioxide and ammonia. Currently, most fish farms are in coastal zones and sheltered areas such as sea lochs and inlets (The Scottish Government, no date a).

Offshore finfish aquaculture is currently dominated by Norway and China. Norway is the world leader in salmon aquaculture exporting 1.1 million tonnes of farmed salmon in 2019 (Fish Farming Expert, 2020b). Norway has decades of experience which has given them the skills, technology and finances to be the most competitive and efficient producer of salmon in the world (California Environmental Associates, 2018). This, however, has not prevented them from facing the same issues as other global aquaculture sectors. The Norwegian government realised that coastal and fjord aquaculture sites were reaching their ecological limits. To ensure the continued growth of the Norwegian aquaculture sector, the Norwegian government introduced a 15-year arrangement offering free development salmon aquaculture licences to projects that aim to develop solutions to either the ecological or territorial issues facing the industry. These development licences are granted under the condition that technology developed will be shared to improve the industry. If a fixed set of criteria is met, the licences can be converted into a commercial licence at a cost of $1.05 million USD (Norway Exports, 2016). Introducing the development licence system which removes the $ 5.4 – 6.5 million USD licence fee required to farm salmon has led to multiple offshore finfish solutions being produced by Norwegian companies such as SalMar and Nordlaks (

Table 1).

Table 1: Examples of offshore finfish developments

Site	Company & Location	Environmental Characteristics	Design Type	Design specifics	Yield	Stage	Pros	Specific Issues	Source
Ocean Farm 1	**SalMar.** Norwegian Sea (Frohavet), 5km off the coast of **Norway**.	Not stated	**Offshore salmon cultivation. Platform-like semi-submersible.** 6 nets. Semi-rigid netting. Rigid steel frame. 8 catenary mooring lines holding structure in place.	Height: 68m. Diameter: 110m. Volume 250,000m^2. Designed to withstand wave heights of up to 5m.	1.5 million or 8,000 metric tons of fish in 14 months	First production cycle completed in early 2019 - Salmar reports strong biological results good growth, good quality, fish even sized. Second cycle underway	Fully automated system - requires only 3-4 men to man. Proven in harsh conditions. Semi-rigid structure of net makes it better equipped for the offshore environment as it is less likely to be deformated and will remain intact even if a breakage occurs. Also ensures there is no reduction in net volume. Semi-submersible bodies have relatively small vertical motions because they have a low centre of gravity.	Escaped fish - structure tilted due to a hatch leak. Lengths of netting were up to 18cm under water. Sea lice - reported as present but in numbers less than the average for the area. Situated in fjord area so wastewater, excess nutrients, toxins and disease may be washed back to site. Expensive - large and complex structure.	CBINS (2017 Farı Exp (2017), (2019); SalMar, (2017); The Explorer, (2018); El-Thalji, (2019); Yu *et al.*, (2019); Salmon Business, (2020); Seafood Source, (2020b)

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Havfarm 1 (Stationary Havfarm)	**Nordlaks.** Norwegian Sea (Vesterålen), approx 5km south-west of Hadseløya, **Norway.**	Not stated	**Offshore salmon cultivation. Vessel-like semi-submersible** with a catamaran-like hull. 6 nets. Single-point mooring.	Length: 430m Width: 54m Weight: 33,000 tonnes. 6 cages of 50 x 50m at the surface that reach a depth of 60m. Designed to withstand wave heights of up to 10m	2 million salmon or 10 000 tons of fish	Scheduled to be placed in Norway summer 2020.	Can be raised up out the water to avoid extreme weather. Rotation around single moor point will allow for 'weathervaning' - the ability to move to a favourable angle towards wind, waves and current and to increase the deposit area of waste nutrients as well as reducing stress on the mooring anchor. Rigid structure provides a stable working platform for operations and maintenance.	Steel frame is very large & heavy - costly to transport. Steel is susceptible to structural failure under extreme conditions. Large masses require heavier mooring systems.	Nordlaks, (2018); Ship Technology, 2018; El-Thalji, (2019); Fish Farming Expert, (2020a); Salmon Business, (2020)

Skelwick Skerry	**Cooke Aquaculture Scotland.** East of Skelwick Skerry, North Sound, **Orkney**, ~2.5km from shore	Depth: 50m Relatively offshore high energy site. Significant wave height: 6.6m	**Salmon cultivation. 8 flexible floating cages.**	Cages 130 m circumference. Deep, wide nets with an area of 28,000m^3. Cages made from HDPE.	Not stated	4/8 cages installed as of 08/2019. First cohort of salmon were released in Nov 2018 at 2.5kg and harvested May 2019 at an average weight of 5.5kg.	Relatively offshore site disperses dissolved and particulate waste produced by farm more efficiently. Mortalities very low. Gill health of first cohort very good. Flexible cages can disperse wave/current energy reducing stress on cage & fish.	Flexible cages prone to deformation by strong currents which can reduce net volume and result in escapes.	Fish Farming Expert, (2017a); 'Blueprint for aquaculture in Scotland', (2019)

Earth Ocean Farms	**Earth Ocean Farms.** Baja California, Sur, Sea of Cortez. 31 miles north of La Paz and 2 miles away from the coast. **Mexico.**	Depth: 120 - 220 ft, Very strong currents, Area prone to hurricanes.	**Offshore Totoaba and Pacific Red Snapper cultivation. Fully submersible** Innovasea 'Aquapods'**.**	7 aquapods of different sizes within a 10-grid cell. (true as of May 6, 2016 but company was approved to increase their site from 84 hectares to 342 hectares allowing for space for 40 new aquapods. Anchored on 4 sides.	Not stated	Currently site has multiple cages rearing Totoaba and Pacific Red Snappers.	Reportedly no traceable impact to the marine environment around site. Submersible so can avoid bad weather. When at sea level pen functions as a traditional surface pen making it easy to manage. Cages can be rotated so that portions of the net are exposed to the air to help remove biofouling by drying out. Copper alloy mesh netting used is predator proof.	Submersible cages are quite difficult to operate as a result of being below surface. Operating costs may be higher than industry standard. Lack of visibility when submerged.	FAO, (2010); Aquaculture North America, (2016); Earth Ocean Farms, (2017); EPA, (2019); Seafood Source, (2019); Innovasea, (2020)

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3.3. Offshore shellfish aquaculture

Shellfish aquaculture in Europe is mainly small-scale family-owned enterprises with less than 5 employees (European Commission, 2018). Shellfish aquaculture has been around for centuries, with many early societies harvesting wild shellfish by introducing artificial substrata and transplanting viable species into an accessible area. As shellfish larvae have a free-swimming stage, a supply of juveniles and nutrients in an area can result in a crop forming on the artificial substrates which can be harvested (Stevens *et al.*, 2008). Currently, most shellfish operations still rely on passive spat collection which leads to fluctuations in productions and business uncertainty. For species such as mussels, active collection involves dredging which can negatively impact the environment and wild mussel populations. As a result, commercial mussel seed hatcheries are being developed to ensure mussels can be farmed sustainably (Seafish, 2019f). Hatcheries produce spat that can then be transferred to grow-out lines. This protects wild populations and reduces fluctuations that result from relying on natural spat settlement. This is particularly important in Scotland who experience lower rates of natural settlement compared to sites in the south of England (Adamson, Syvret and Woolmer, 2017).

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Figure 4: Diagram of longlines used to cultivate mussels.

Table 2: Examples of offshore shellfish developments

Site	Company & Location	Environmental Characteristics	Design Type	Design specifics	Yield	Stage	Pros	Specific Issues	Sources
Offshore Shellfish Ltd	**Offshore Shellfish Ltd.** Lyme Bay, coast of South Devon, 3-6 miles offshore. **UK.**	Area doesn't have very high primary production and has relatively little stratification or HABs.	**Offshore farming of Blue mussel** *(Mytilus edulis*), rope cultured mussel farm.	250 longlines in place - each longline carries ~ 2,000 m grow-out rope.	5 kg/m - 20 kg/m. Approx. average of 10kg/m or 20 tonnes per headline. Potential production of 10,000 tonnes per 1540 ha assuming an average age at harvest of 18 months and a complete turnaround of gear every two years.	Farm has been in operation since 2014. Farm is about 35% built so far - aim to have ~ 250 longlines across 3 sites spread across 3 sites covering an area of 1540 ha to ensure longlines are well spaced	Low density cultivation at offshore site is beneficial for quality, rate of growth and meat content.	Increasing density could lead to problems as tightly spaced ropes are difficult to manage in offshore environment. Access to the farm is at times limited by weather conditions.	Personal communication: John Holmyard, Offshore Shellfish Ltd; Sheehan Research Group, (2013); Fish Farming Expert, (2016); The Fish Site, (2018); Offshore Shellfish LTD, (2020)

Whakatohea Mussels Limited	**Eastern Sea Farms Limited.** Opotiki, 8km off the coast, **New Zealand.**	Depth: 40 m Free from major shipping traffic. Waves: mean Hs peak period 1.7m / 7.4s. Max Hs / Peak period 6.5 m /12 s. Median wind speed: 10 kts. Max wind speed & direction 45 kts (WSW)	**Offshore farming of NZ Green-Lipped mussel** (*Perna canaliculus*)	3,000m of culture rope across 3 backbone lines spread across 3,800 ha of sea.	330 longlines as of 2017 with a total of 1000 lines permitted by current lease.	First two seasons saw good results: 95 millimetres in length in 14 months with yields of over 9 kgs per meter of culture rope.	Low density cultivation available at offshore site is beneficial for quality, rate of growth and meat content. beneath site.	Costly improvements are needed to the local harbour so mussel barges can work out of the local area.	Aquaculture New Zealand, (2011); Whakatohea Mussels Opotiki Limited, (2014); Knight *et al.*, (2017); Hin Group, (2018)
Catalina Sea Ranch	**Catalina Sea Ranch.** San Pedro Shelf, 6 miles offshore. California, **USA.**	Depth: 150 ft. Area: 100-acres.	**Offshore aquaculture facility** investigating offshore cultivation of multiple species.	Mediterranean mussel (*Mytilus Galloprovincialis*) cultured on sub-surface rope loops 20 feet below the sea surface supported by floats. 40 backbone nylon ropes tied to long metal anchor poles bored into seafloor.	~ 5lbs on every foot of rope. 8 - 10 months after they were planted mussels reached market size of 3 inches long.	Filed for bankruptcy in December 2019.		Claims that failings were due to the FDA: large disparities between state and federal shellfish biotoxin testing. Testing very costly. Issues navigating a new regulatory system. Lack of extensive data regarding biotoxins in chosen site. Lack of capital. Harvesting assets that were too small.	Catalina Sea Ranch, (2017); Undercurrent News, 2020)

Operating offshore farms Whakatohea Mussel and Offshore Shellfish LTD are both low-density cultivation farms. Instead of heavily stocking the sites and maximising profit, both sites have opted to cultivate mussels in low densities. This increases the food availability for the cultivated mussels and ensures there is no food deficit in the area for non-cultivated species (Hin Group, 2018; Offshore Shellfish LTD, 2020). Tightly spaced ropes with high stocking density result in a lot of equipment being in the site which can be difficult to manage in the offshore environment (Personal Communication: John Holmyard, Offshore Shellfish Ltd.).

3.4. Offshore colocation

MUPs are currently in the research and development phase with plenty of concepts but few test sites despite considerable interests (Leira, 2017). Three funded MUP research projects were initiated by the European Commission including the Mermaid project which ran from 2012-2016. This project joined 28 partner institutes from universities, research institutes, industries and small and medium enterprises to develop concepts for offshore MUPs joining sectors including energy, aquaculture and platform related to transport (Mermaid project, 2012). The project aimed to theoretically examine new MUP concepts for specific areas to address different physical conditions to optimise the use of ocean space (Figure 5) and focused on economic efficiency, social equity and environmental and ecological sustainability (Koundouri *et al.*, 2017).

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Figure 5: Map of the four sites considered by Mermaid project (Koundouri et al., 2017).

Projects experimenting with the combination of offshore wind and aquaculture in Europe are considering both finfish and shellfish aquaculture (

Table 3). These are all small-scale research projects or pre-commercial pilots. For large scale MUPs to become a reality, a lot of cooperation between different sectors will be required which may slow down the development and construction process. Blue growth sectors are also in various stages of development and growth – offshore wind is a fairly well-developed sector, whereas offshore aquaculture is still in the research and development phase. A lot of work is still required to develop methods and technology that will allow sectors within an MP to benefit from the synergy and function optimally (DNV.GL, 2019).

Table 3: Examples of MUP projects combing wind and aquaculture

Site	Company & Location	Environmental Characteristics	Design Type	Design specifics	Yield	Stage	Pros	Specific Issues	Sources
C-Power wind farm	**Belgian Offshore Platform (BOP) & Edulis Project.** Thornton Bank, **North Sea,** 30 km from the Belgian coastline	Depth: 14 - 28 m Area: 19.84 km^2. Soft sediment seabed is composed of medium sand (mean median grain size: between 350 and 500 µm. Average residual water transport is oriented to the northeast	**Offshore wind farm trialling Blue Mussel** (*Mytilus edulis*) **cultivation** semi-submerged longlines	54 wind turbines installed - generates ~1.05 GWh yearly. 700m between turbines. Longline backbones 58m long and held 5m beneath surface- held in place by weight anchors.	Not stated	R&D project to study the feasibility of mussel farms in offshore wind turbines looking at both mussel seed capture & growth as well as the environmental conditions faced by the farms. Longlines deployed May 2017.	Samples of species biofouling on the wind turbines when first installed showed *Mytilus edulis* naturally occurred throughout sampling within the area along with other commercially valuable species	Restrictions regarding where lines can be placed due to pre-existing wind turbines and the need to access them.	BOP, (no date); Douvere, (2010); ICES, (2011); Kerckhof *et al.*, (2012); Degraer, Brabant and Rumes, (2017); Holm, Buck and Langan, (2017); C-Power, (2020)

Belwind farm	**Belgian Offshore Platform (BOP) & Edulis Project.** Bligh Bank, **North Sea,** 46 km from Belgian shore	Depth: 15 to 37 m, Area: 17km2. Soft sediment seabed is composed of medium sand (mean median grain size: between 350 and 500 µm	**Offshore wind farm trialling Blue Mussel** (*Mytilus edulis*) **cultivation** semi-submerged longlines	56 turbines with a total capacity of 171 MW.	Not stated.	R&D project measuring the forces exerted by the sea on longlines to determine the minimum requirements for a mussel culture system to optimise future designs. Longlines deployed November 2017.	Samples of species biofouling on the wind turbines when first installed showed *Mytilus edulis* naturally occurred occasionally during sampling within the area along with other commercially valuable species	Restrictions regarding where lines can be placed due to pre-existing wind turbines and the need to access them.	BOP, (no date); Kerckhof *et al.*, (2012)
FLOCAN 5	**COBRA BESMAR & ACS.** South-East coast of **Gran Canaria**, 5.2 km from shore, North Atlantic Ocean	Depth: 40 - 200 m for turbines, 40m for aquaculture. More than 60% of the area have sediment formed by medium-coarse sand. Annual average wind speed 23.3-25.3 km/h (6.5-7.0 m/s). average wave period of Tm: 5.21 s, and an average wave height Hs: 1.05 (m).	**Offshore floating wind farm & framing of Sea bass** (*Dicentrarchus labrax)*	5 floating turbines each rated at 5 MW each. 6 fusion type offshore aquaculture cages. 2 submarine power cables linking wind farm to an offshore floating substation. Wind and aquaculture anchored to seabed by tension mooring.	Wind: 25 MW total capacity Aquaculture: 40 tons capacity	Pre-commercial pilot with plans to expand to 25 floating wind turbines rated 5MW each and 24 fusion type offshore aquaculture cages with 40 tons sea bass production capacity each across 23 km3.	Wind farm provides calmer water for cages = increased cage longevity, reduced stress on fish. Simple share of space - no physical connection. Pre-existing sea bass farm - already proven to work in this site. The area is one of the highest energy sites in Europe.	Adverse weather may prevent access during construction/installation. Potential damage to the local environment as a result of moorings being installed.	BVG Associates, (2016); MARIBE, (2016); Dalton, Johnson and Masters, (2018)

4. Potential aquaculture species

4.1. Macroalgae

Currently, 4 species of macroalgae are being considered as candidates for offshore cultivation in UK waters (CEFAS, 2019). Four main environmental variables are considered important for macroalgae cultivation (Table 4). Macroalgae can be cultivated on simplistic structures and require low maintenance and do not require additional inputs such as food and medication. Cultivation of macroalgae has several environmental benefits, for example, production of macroalgae for use as biofuel can reduce the use of fossil fuels. Cultivation can also improve water quality as macroalgae intake inorganic nutrients from the environment which are removed from the ecosystem upon harvesting (Burg *et al.*, 2013) however, due to offshore sites often having low nutrient concentrations this impact may be minor (Söderqvist *et al.*, 2017).

Commented [KM22]: This is now a very different section which focuses on asking the question 'which species might be suitable for cultivation' and uses information available in the literature or in the public domain to address this question.

Table 4: Optimal conditions for macroalgae cultivation including sea surface temperature (SST), salinity, light depth (Kd(PAR) 10% light depth) and nutrient level (nitrates and nitrites TOxN) (CEFAS, 2019).

Commented [KM23]: Nice clear informative table with detailed legend describing the contents. It is also important that when abbreviations are used that they are explained in the legend or in a footnote at the bottom of the table. While the abbreviation might be familiar, you have to imagine that a total non-expert was reading the text.

Species	**Sugar kelp (*Saccharina latissima*)**	***Laminaria digitata***	**Winged kelp (*Alaria esculenta*)**	**Dulse (*Pal* *palmata*)**
Minimum SST (°C)	>5	>5	>4	>6
Maximum SST (°C)	<16	<16	<16	<15
Minimum Salinity	>24	>20	>20	>32
Kd(PAR) 10% light depth (m)	>2	>2	>2	>1
Winter TOxN (mmol/m3)	>10	>10	>10	>10
Current (m/s)	0.1-1.5	moderately exposed - strong currents	exposed & very exposed sites	sheltered or moderately exposed areas

Evaluation of the suitability of the species being considered and other considerations can be found in Table 5. Macroalgae cultivation has shown high production potential in offshore environments compared to inshore areas as a result of stratification causes nutrient limitations in coastal areas (Broch *et al.*, 2019). Although in some areas macroalgae may settle naturally on longlines, an onshore hatchery to cultivate seedlings to transfer to offshore sites can make production more stable and secure. However, onshore infrastructure requires high capital investment (Rolin *et al.*, 2016).

Table 5: Evaluation of suitability and considerations for offshore macroalgae cultivation.

Commented [KM24]: Another very useful comparative table to enable an evaluation of the potential of different species for cultivation in the context of offshore windfarm co-location

	Technology readiness	Suitability for offshore	Commercial considerations	Additional information	Sources
Saccharina latissima (sugar kelp)	Cultivated on suspended rope/textile	**Suitable - low maintenance and requires no additional inputs.** Well suited to oceanic waters out with coastal zones. Proven to grow in North Sea conditions. Cultivated during a study in exposed & deep water in the Faroe Islands.	**Low value hence requires high biomass production.**	More susceptible to herbivores and biofouling as is less leathery than other species being considered. Short living species that has to be grown annually from fresh seedlings.	Burg *et al.*, (2013); Bak, Mols-Mortensen and Gregersen, (2018); Ferdouse *et al.*, (2018); Azevedo *et al.*, (2019); Broch *et al.*, (2019); CEFAS, (2019)
Laminaria digitata (oar weed)	Cultivated on suspended rope/textile	**Suitable - low maintenance and requires no additional inputs.** Already cultivated under North Sea conditions. Most robust out of the 4 species being considered.	**Low value hence requires high biomass production**	Grows constantly - even under low temperatures during winter. Can be harvested more than once - fewer seedlings required.	Edwards and Watson, (2011); Burg *et al.*, (2013); Rolin *et al.*, (2016), (2017); CEFAS, (2019)
Alaria esculenta (winged kelp)	Cultivated on suspended rope/textile	**Suitable - low maintenance and requires no additional inputs**. Cultivated during a study in exposed & deep water in the Faroe Islands.	**Low value hence requires high biomass production**		Burg *et al.*, (2013); Bak, Mols-Mortensen and Gregersen, (2018); CEFAS, (2019)
Palmaria palmata (dulse)	Cultivated on suspended rope/textile	**Suitable - low maintenance and requires no additional inputs.** Currently has not been cultivated under North Sea conditions**.**	**Low value hence requires high biomass production**	Slow-growing species. Can be propagated vegetatively which reduces the requirement for seedling production.	Burg *et al.*, (2013); CEFAS, (2019)

Macroalgae is considered a good candidate for co-culture alongside bivalves. There are limited interactions between the two as macroalgae feed on inorganic nutrients and bivalves feed on organic nutrients. There are some small interactions between the two species as bivalves produce inorganic nutrients through the excretion of metabolic waste products which can be utilised by macroalgae. This may mitigate against the competition between the microalgae bivalves feed on and the macroalgae as both require inorganic nutrients (Burg *et al.*, 2013). The reduction of nutrients in the area may increase light penetration which could benefit benthic species; however, it is also possible that the introduction of these species into an area will reduce nutrient availability enough to negatively affect wild organisms in the area. Interactions between the cultivated species and each other as well as the environment make the net effect on biodiversity difficult to establish (Söderqvist *et al.*, 2017).

Commented [KM25]: An 'English' blooper here, algae are plural of course hence the 'is' should be an 'are'. Checking your text for spelling, grammar and punctuation are critical. This thesis has very few errors throughout. At the end of the day we are all human. Also, remember that predictive text (as you type) can insert nonsense into your narrative without you realising. It is always a good idea to get someone else to read your work, you become 'blind' to errors after seeing the same text over and over.

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4.2. Finfish

Scotland's aquaculture sector is dominated by finfish aquaculture in terms of both weight and value. Most finfish aquaculture in Scotland takes place at sea with Atlantic salmon (*Salmo salar*) dominating the Scottish aquaculture sector (The Scottish Government, no date a). Scotland is the third-largest global producer of salmon behind Norway and Chile (Scottish Wildlife Trust, 2018). Although salmon is the main species cultivated, Rainbow Trout (*Oncorhynchus mykiss*), Brown trout (*Salmo trutta trutta*), Halibut (*Hippoglossus hippoglossus*), Atlantic cod (*Gadus morhua)* and Haddock (*Melanogrammus aeglefinus)* have all been produced in Scotland in small quantities (The Scottish Government, no date a).

Finfish species that are considered suitable for offshore cultivation in Scottish waters alongside the key environmental parameters required for growth are listed in Two paragraphs removed here.

Atlantic cod is found in a range of cold-water temperatures and has a relatively high growth rate in colder conditions. Like the sea trout, it is a robust species that can withstand temperatures from ~0°C to 20°C. Atlantic cod is one of the most important commercially fished species but due to overfishing has been listed as vulnerable on the IUCN red list. The unsustainable fishery paired with high demand resulted in the development of aquaculture techniques for the species. The production of juvenile fish to be transferred to sea cages to mature is the limiting factor of the industry as there are not as many hatcheries as there are for other commercial species (CEFAS, 2019). The market size of the species is 2-4 kg with individuals reaching market weight 24-36 months after hatching. Production costs per kg can be very similar to the market price for cod with many companies failing to make any profit from cultivation of the species (FAO, 2020d).

Turbot (*Scophthalmus maximus*) and hake (*Merluccius merluccius*) are both prominent in the UK market, however, turbot is a warm water flatfish that is inappropriate for UK waters despite its high market value. Similarly, hake has a high market value, but little is known about hake biology and a lot of research and development would be required to develop a functioning hatchery as well as rearing methods (James and Slaski, 2006). As a result, both hake and hurbot are not considered further in this thesis.

Halibut are also considered incompatible for offshore cultivation. Halibut are bottom-dwelling species that requires a large surface area to lie on. They are a slow-growing species that take ~4 years to reach market size and sexual maturity after 10-14 years. Halibut have a complex life cycle which can be difficult to replicate in a farm setting – the larvae have high nutritional needs that can lead to improper development if not kept very stable and juveniles can be very aggressive and require specialised feed and light regimes to prevent aggressive behaviour. Halibut also have a declining UK market with sales in 2018 of £1.15 million which was a 2.7% decrease from 2017. The volume of UK retail sales also saw a decline of -4.5% in 2018 (Seafish, 2019a).

Table *6*. Salmon is successfully farmed in Scotland with a well-established market and is Scotland's largest food export by value. Salmon has a high market price accounting for UK retail sales of £1,056 million in 2018 with an average price of £16.98 per kg. The life cycle of salmon is well understood and farming replicates the natural life cycle of the species. Initial life stages take place in freshwater until they are 8-16 months old when they are transferred into seawater to continue to grow until they reach market size. Market size for salmon is 2 kg+ and takes up to 2 years (Seafish, 2019b).

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Table 6: Optimal conditions for finfish species considered suitable for offshore cultivation in Scottish waters including sea surface temperature (SST), salinity & dissolved oxygen (CEFAS, 2019).

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Species	**Atlantic salmon (*Salmo salar*)**	**Rainbow trout (*Oncorhynchus mykiss*)**	**Brown (sea) trout (*Salmo trutta trutta*)**	**Atlantic cod (*Gadus morhua*)**
Minimum SST (°C)	>6	>4	>4	>4
Maximum SST (°C)	16-18	12-17	12-17	12-17
Minimum Salinity	22-34	0-24	33-40	0-24
Maximum Salinity	22-34	0-24	33-40	0-24
Dissolved Oxygen (mg/L)	>5	>6	>6	>6

Evaluation of the suitability of the species being considered and other considerations can be found in

Table 7. Currently, offshore finfish cages are at a pre-commercial stage and the sector is still in the research and development (R&D) phase, however, there are several other constraints. Finfish require much more husbandry compared to macroalgae and shellfish including feeding, grading, harvesting cleaning and monitoring. All of these tasks must be carried out at the offshore site where the conditions are often dangerous and unpredictable. Automation of some aspects of husbandry - such as feed and cage cleaning – is in development. Grading and harvesting are labour intensive tasks that usually involves moving the fish into a smaller cage so they can all be inspected. Again, this requires having access to the site and conditions to be safe for crew carrying out the task which may be difficult and unpredictable in the offshore environment (Forster, 2013).

There are also environmental concerns associated with rearing finfish offshore. Chemical usage is associated with fish farming including antibiotics, pesticides, herbicides, hormones, anaesthetics, pigments, minerals and vitamins (Cole *et al.*, 2009). Medication is often used as disease and parasites are common in cultivated finfish which can cause a reduction in stock and can be passed on to wild fish populations (Cole *et al.*, 2009)……

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The use of 'cleaner fish' species that eat sea lice and dead skin (such as ballan wrasse (*Labrus bergylta*) and lumpsuckers) is a method that avoids the introduction of chemicals into the area. Ballan wrasses are particularly effective as they eat lice in temperatures lower than other wrasse species. The main issue associated with cleaner fish use is that they are very few farms who cultivate them. This puts a lot of pressure on natural stocks (Bellona, 2013). …..

Part of paragraph removed here.

Feed and waste introduced into an area by finfish aquaculture can cause a build-up of excess nutrients (such as organic nitrogen and phosphorous) which can result in organic pollution and eutrophication. When paired with chemical pollution this can lead to algal blooms, depletion of oxygen, reduction in water quality and habitat degradation

These are all issues that have been faced by coastal finfish aquaculture operations, and although less likely to occur in the deeper waters of the offshore environment effective management practices must be employed to reduce negative environmental effects. ……

Part of paragraph removed here.

Areas that host finfish aquaculture sites can also suffer as a result of habitat modification. Habitat modification can be either direct or indirect. Direct modification can include wild species being obstructed from their natural habitat by aquaculture structures (i.e. a cluster of cages) or predators being attracted to the area by the large aggregation of prey. Predators attracted to the sites can become entangled in nets or mooring lines and die. Acoustic deterrents have been used to deter predators from aquaculture sites, but these can cause disorientation, pain or hearing loss. Ensuring that aquaculture sites are far away from seal haul-out sites and ensuring mooring lines and cages are properly tensioned or thick rope is used can reduce the risk of attraction and entanglement (Goldburg, Elliott and Naylor, 2001).

Table 7: Evaluation of suitability and considerations for offshore finfish cultivation

Species	Technology readiness	Suitability for offshore	Commercial considerations	Other considerations	Sources
Atlantic salmon (*Salmo salar*)	**Cultivated in sea cages**, hatchery and biology understood.	**Suitable** for environment. Offshore finfish cages still pre-commercial - R&D phase.	**Well established global market** - high demand and value	**Additional inputs required**, loss of stock (escapes or theft), predators	James, M.A and Slaski, (2006); California Environmental Associates, (2018); El-Thalji, (2019); Seafish, (2019b)
Rainbow trout *(Oncorhynchus mykiss)*	**Cultivated in sea cages**, hatchery and biology understood.	**Suitable** for environment. Offshore finfish cages still pre-commercial - R&D phase.	**Smaller market demand.** Robust species - low risk. Can be cultivated at high densities.	**Additional inputs required** (including importing eggs), loss of stock (escapes or theft), predators	California Environmental Associates, (2018); Seafish, (2019c); FAO, (2020a)
Brown (sea) trout **(***Salmo trutta trutta*)	**Cultivated in sea cages**, hatchery and biology understood.	**Suitable** for environment. Offshore finfish cages still pre-commercial - R&D phase.	**Smaller market demand.** Robust species - low risk.	**Additional inputs required,** loss of stock (escapes or theft), predators	Scottish Natural Heritage, (no date); James, M.A and Slaski, (2006; FAO, (2020b)
Atlantic cod (*Gadus morhua*)	**Cultivated in sea cages**, hatchery and biology understood.	**Suitable** for environment. Offshore finfish cages still pre-commercial - R&D phase.	**High market demand but low value** - unlikely to be profitable. Limited hatcheries.	**Additional inputs required,** loss of stock (escapes or theft), predators	James, M.A and Slaski, (2006; FAO, (2020c)

4.3. Shellfish

Scotland's shellfish aquaculture sector mainly produces blue mussel (*Mytilus edulis*) but native (flat) oysters (*Ostrea edulis*), Pacific oysters (Crassostrea giga), king scallops (Pecten maximus) and queen scallops (*Aequipecten opercularis*) are also cultivated (The Scottish Government, 2019). Farming mainly takes place in sheltered sea lochs and voes (The Scottish Government, no date b). The sector is in a period of decline with mussel production in 2018 totalling 6874 tonnes - a 16% decrease from the previous year – 75% of which was from Shetland. This is due to problems identifying and securing new sites suitable for shellfish cultivation and the excessively expensive and inconsistently enforced planning processes required to secure sites (MARITEK, 2019). Shellfish can be a good option for offshore cultivation as they have no additional requirements and low husbandry requirements, unlike finfish. They also require less capital as the equipment required is much simpler than that involved with finfish aquaculture. Furthermore, most species already have a well-established market unlike macroalgae (Hambrey and Evans, 2016).

Optimal conditions for potentially appropriate shellfish species are listed in Table 8. ….

Part of paragraph removed here.

However, large aggregates of cultivated shellfish can reduce food availability for wild species in the area. They can also take in and bioaccumulate harmful toxins and bacteria from the water column. For example, if bivalves are in an area where there is a harmful algal bloom, they will feed on algae which contain biotoxins that are dangerous to human health. In the most extreme scenario, this can result in paralytic shellfish poisoning and cause death. …..

Part of paragraph removed here.

Table 8: Optimal conditions for shellfish species considered suitable for offshore cultivation in Scottish waters including sea surface temperature (SST), salinity, dissolved oxygen & chlorophyll concentration (CEFAS, 2019).

Species	**Blue mussel (*Mytilus edulis*)**	**Native oyster (*Ostrea edulis*)**	**Pacific oyster (*Crassostrea gigas*)**	**Manila clam (*Ruditapes philippinarum*)**	**King scallop (Pecten maximus)**
Minimum SST (°C)	>8	>10	>15	>5	>10
Maximum SST (°C)	12-17	12-20	15-25	18-23	10-17
Minimum Salinity	>18	>25	>20	>15	30-35
Maximum Salinity	25-30	25-35	25-35	25-35	30-35
Dissolved Oxygen (mg/L)	>7	>8	>8	>2	>8
Chlorophyll (µg/L)	>6	>8	>8	>2	<20

Other issues associated with shellfish aquaculture include disease and parasites. Disease is one of the biggest risks facing the shellfish industry. An outbreak can cause huge economic repercussions through the loss of stock and in most cases, there are no known curative measures. For example, *Marteilia refringens* is a protozoan parasite which causes mareiloisos in blue mussels. The disease depletes the resources of the mussel ultimately resulting in death (Fox *et al.*, 2020). Issues can also arise from predator attraction. Similar to finfish, large aggregates of shellfish can attract predators who may become entangled in aquaculture equipment. However, this can improve local biodiversity by taking pressure off of wild species. An evaluation of potential species and considerations can be found in

Table *9*.

Table 9: Evaluation of suitability and considerations for offshore shellfish cultivation

Species	Technology readiness	Suitability for offshore	Commercial considerations	Other considerations	Sources
Crassostrea gigas (Pacific oyster)	**Cultivated both in the water column and as bottom culture**. hatchery understood.	**Not suitable** - best suited to shallow, nutrient-rich & sheltered sites	**High production costs** due to slow growth. Few hatcheries in Scotland.	**High demand outweighs seed production.** Invasive species - relatively little known about impact on native species. **Disease -** high levels of summer mortality in France and the US. Parasites. Predators.	James and Slaski, (2006); Hambrey and Evans, (2016); Seafish, (2019c); Barillé *et al.*, (2020); FAO, (2020a)
Ostrea edulis (native (flat) oyster)	**Cultivated both in the water column and as bottom culture**. Hatchery understood but more difficult than other species.	**Not suitable** - best suited to shallow, nutrient-rich & sheltered sites	**High value but high production costs.** Few sources of spat.	**Less robust than Pacific oyster**. **Disease** - no curative measures available. Parasites. Predators.	James and Slaski, (2006); Ferreira *et al.*, (2009); Hambrey and Evans, (2016); CEFAS, (2019); Seafish, 2019c; FAO, (2020e)
Mytilus edulis (blue mussel)	**Cultivated both in the water column and as a bottom culture**. Hatchery in the developmental phase.	**Suitable -** already cultivated offshore	**Low value** but high demand with well-established market**.** Large-scale production still depends on natural spat - **unpredictable fluctuations in yield**	**Production costs of rope culture are significantly greater** than bottom culture practised in Europe. Very tolerant to fluctuations in environmental conditions Disease. Parasites. Predators.	James and Slaski, (2006); Sheehan Research Group, (2013); Hambrey and Evans, (2016); CEFAS, (2019); Seafish, (2019e)
Ruditapes philippinarum (Manila clam)	**Bottom culture.** Hatchery understood.	**Not suitable -** requires intertidal sites sheltered from extreme wind, wave and tidal action.	**Low demand** - mainly exported	**Disease** - no curative methods available. Parasites. Predators,	James and Slaski, (2006); Hambrey and Evans, (2016); CEFAS, (2019); FAO, (2020f)

Pecten maximus (King scallop)	**Cultivated both in the water column and as a bottom culture.** Hatchery understood.	**Not suitable** - high maintenance requirements.	**Require low stocking density** - expensive to use suspended cultivation methods that give them enough space to avoid mortality caused by overcrowding. Few hatcheries.	**Long grow-out period.** More sensitive to environmental conditions than other species. Wave action can cause stress and reduce growth rate. Disease. Predators. Parasites.	Laing, (2002); James and Slaski, (2006); Hambrey and Evans, (2016; Seafish, (2019e)
Aequipecten opercularis (Queen scallops)	**Cultivated both in the water column and as a bottom culture.** Hatchery understood.	**Not suitable** - high maintenance requirements.	**Require low stocking density** - expensive to use suspended cultivation methods that give them enough space to avoid mortality caused by overcrowding. Few hatcheries.	**Long grow-out period**. More sensitive to environmental conditions than other species.	Laing, (2002); James and Slaski, (2006); Hambrey and Evans, (2016; Seafish, (2019e)

5. Environmental characteristics of potential co-location sites

To evaluate the potential for co-location of offshore wind and aquaculture 9 sites around mainland Scotland were selected. Sites chosen are shown in Figure 6. Sites were chosen based on the latest phase of seabed leasing from Crown Estate Scotland. On the 10th of June 2020, Crown Estate Scotland opened an online portal providing information for potential applicants who wish to lease areas of Scotland's seabed for the development of offshore windfarms. Crown Estate Scotland estimates investment in Scottish offshore windfarms could surpass £8bn and will generate enough electricity to power every house in Scotland (Renews.biz, 2020). A range of sites around mainland Scotland were chosen to cover the various conditions of Scotland's seas to evaluate suitable areas for a co-location development.

Diagram removed

Figure 6: Map of sites chosen to evaluate the potential for co-location of offshore wind and aquaculture in Scottish seas. Sites were chosen based on Crown Estate Scotland's phase 4 leasing sites. Sites around mainland Scotland were chosen to cover the varying conditions to identify the best area for co-location development.

For the purpose of this thesis, only mussels were considered as candidates for offshore co-location. Macroalgae was not considered due to the high costs associated with offshore cultivation – macroalgae is low value and requires high biomass so it is unlikely that monoculture would be profitable offshore. Finfish were not considered as offshore cage technology is still in its infancy and requires higher initial capital investment comparative to other potential species. Finfish also have higher husbandry requirements, and automation of these are still in the R&D phase. Mussels have been selected as they are already cultivated in the offshore environment (Table 2;

Table 3), require no additional inputs such as feed and require little maintenance.

5.1. Data collation

Environmental factors important for offshore infrastructure and mussel farming were identified from CEFAS, (2019) and include seafloor sediment, depth, current, wind speed, wave height, sea surface temperature, surface salinity, food availability & dissolved oxygen. Data was collected from a range of sources listed in Table 10.

Commented [KM27]: The prior elements of the dissertation required an extensive trawl through the literature resulting in a tabular collation of information for ease of reporting.

In this section, actual environmental data from publicly available resources is acquired and integrated into a Geographic Information Systems (GIS) package.

Where possible, data was analysed using QGIS (version 3.12) to examine conditions within the sites. This data was then presented as a map so the range of conditions in Scottish waters could be seen.

When this was not possible, data was taken directly from the online source. In some cases, data was only available for an area of the Scottish sea, so the data used was from the area each site was in as defined by the source. Methods used for analysing each environmental parameter are listed in Table 10. Environmental factors considered likely to affect offshore infrastructure are seafloor substrate, wave height, current, wind speed and depth. Factors considered important for mussel cultivation are sea surface temperature (SST), salinity, dissolved oxygen, chlorophyll a, particulate organic matter and total particulate matter. Optimal variables for mussel cultivation are listed in Table 8.

Commented [KM28]: Nice use of cross referencing to the information which underpins the rationale presented here.

In order to visualise the similarity in environmental conditions among offshore locations, environmental data (Table 10) was normalised and a resemblance matrix constructed based on Euclidean distance. The latter was used to construct a multi-dimensional scaling plot. These analyses were undertaken using PRIMER (version 7).

Commented [KM29]: This is actually a statistical analysis of the environmental data to visualise the similarity among the different sites examined in terms of the prevalent environmental conditions at each site. As such this should really be under a separate heading ‘statistical analysis’. Given the structure of this these there could have been two sections in the report that dealt with different statistical analyses.

Table 10: Environmental factors used for evaluation of sites for wind farm and mussel farm co-location. Parameters are listed along with their units, additional information and source.

Commented [KM30]: This type of data source listing might seem 'boring' but it is essential if someone else wants to repeat the analyses undertaken here. This is best practice in operation.

Parameter	Unit	Additional information	Source
Seafloor Sediment	Folks 16 hierarchy	Downloaded and analysed using QGIS	https://hakku.gtk.fi/en/locations/search?location_id=166
Depth	Metres (m)	Downloaded and analysed using QGIS	https://download.gebco.net
Peak current speed of a mean neap tide	Metres per second (m/s)	Downloaded and analysed using QGIS	https://www.renewables-atlas.info/downloads/
Peak current speed of a mean spring tide	Metres per second (m/s)	Downloaded and analysed using QGIS	https://www.renewables-atlas.info/downloads/
Mean wind speed at 80m height	Metres per second (m/s)	Downloaded and analysed using QGIS	https://www.renewables-atlas.info/downloads/
Wave Height	Metres (m)	Downloaded and analysed using QGIS	https://www.renewables-atlas.info/downloads/
Sea surface temperature (SST)	Degrees Celsius (°C)	Data point closest to site used: XX - Clyde Sea. XXX - Malin Shelf Inner. XXXX - North Coast South. YYY, YYYY - Offshore North North Sea. XXXXX, YY, ZZZ - North East Coast. ZZ - South East Coast.	https://data.marine.gov.scot/dataset/annual-cycles-physical-chemical-and-biological-parameters-scottish-waters
Surface Salinity	Practical salinity scale (psu)		
Chlorophyll a	micrograms per litre (ug/L)	Not downloadable - values recorded directly from source.	https://www.oceancolour.org/portal/
Dissolved oxygen	Milligrams per litre(mg/L)	Not downloadable - values recorded directly from source. Only winter values used as summer data area too close to coast to be representative of offshore conditions.	https://ec.europa.eu/maritimeaffairs/atlas/maritime_atlas/#lang=EN;p=w;bkgd=5;theme=122:0.75;c=-649110.0385997512,7957894.5123842545;z=6
Particulate organic matter (POM)	Milligrams per litre(mg/L)	Not downloadable - values recorded directly from source. Figure 3, map 5 from source used for POM values	https://www.sciencedirect.com/science/article/pii/0077757987900020
Total particulate matter (TPM)	Milligrams per litre(mg/L)	Values recorded directly from source. Data point closest to site used: XX, XXX - Irish Sea. XXXX - Scottish Continental Shelf. XXXXX, YY, YYY, YYYY, ZZ, ZZZ - Northern North Sea	https://moat.cefas.co.uk/ocean-processes-and-climate/turbidity/

5.2. Seafloor sediment

Seafloor sediment is relevant as is affects the type of anchoring or mooring system that must be used for offshore infrastructure (CEFAS, 2019). Anchoring systems must hold offshore structures in place and be robust enough to withstand the environmental conditions of the site. Seafloor substrates and sites are shown in Figure 7.

Diagram removed

Figure 7: Seafloor substrate of Scottish seas and potential co-location sites. Data from: https://hakku.gtk.fi/en/locations/search?location_id=166 [Accessed 22/05/2020].

CEFAS (2019) states that for suspended culture of bivalves any substrate is suitable for mooring longlines. Oregon Wave Energy Trust, (2009) carried out an anchoring and mooring study applying industry knowledge regarding anchoring and mooring techniques for wave energy conversion devices. Anchor types examined in the study are shown in Figure 8. According to the study deadweight and pile anchors would both be suitable for the seafloor substrate in all sites examined.

Diagram removed.

Figure 8: Anchor types commonly used for offshore infrastructure (Oregon Wave Energy Trust, 2009).

5.3. Depth

Bathymetry can affect the type and cost of engineering required for offshore infrastructure. Minimum and maximum depth of sites is listed in Table 11. Deeper sites will be more expensive for offshore development. At deeper sites further offshore (such as YY, YYY, YYYY, ZZ and ZZZ) it may be better to use floating wind turbines instead of bottom-fixed turbines (Figure 9). Fixed turbines are restricted to water depths of less than 50m which has previously prevented the wind industry from accessing the strong and more consistent offshore wind environment (IRENA, 2016). Floating turbines also offer environmental benefits compared to fixed turbines are they have less interaction with the seabed during installation and decommissioning.

Table 11: Minimum and maximum depth of potential co-location sites. Data from: https://download.gebco.net [Accessed 22/05/2020]

Commented [KM31]: Simple but important table with clear legend and source of information.

Site	Depth (m)	
	Minimum	Maximum
XX	15	75
XXX	20	90
XXXX	45	100
XXXXX	40	100
YY	55	103
YYY	85	140
YYYY	70	115
ZZ	60	130
ZZZ	60	100

Figure 9: Example of bottom-fixed and floating wind turbines. Available from: https://www.ideol-offshore.com/en/floating-offshore-wind [accessed: 11/07/2020].

5.4. Current Speed

Current speed affects both offshore infrastructure and mussel cultivation. Structures must be robust enough to withstand the currents of an area. Currents are also responsible for transporting chlorophyll and organic materials that mussels feed on into the area – sites with higher current speeds are likely to be more productive as depleted food sources will be replenished faster than areas with slower current speeds. XX has the highest average peak speed of a mean spring tide with a speed of 1.43 m/s (Figure 10). All other sites showed very little variation with average speed ranging from YYY with the slowest speed (0.32 m/s) to XXX with the second highest speed (0.65 m/s). Highest average peak speed of a Mean Neap tide (Figure 11) followed the same pattern – XX had the highest average speed (0.74 m/s) while all other sites showed little variation with average speed ranging from YYY with the slowest speed (0.16 m/s) to XXX with the second highest speed (0.32 m/s).

Diagram removed

Figure 10: Peak current speed (m/s) of a Mean Spring tide. XX has the highest average current speed (1.43 m/s), while YYY has the slowest average speed (0.32 m/s). Data from: https://www.renewables-atlas.info/downloads/ [Accessed 22/05/2020]

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Figure 11: Peak current speed (m/s) of a Mean Neap tide. XX has the highest average current speed (0.74 m/s) while YYY has the slowest average current speed (0.16 m/s). Data from: https://www.renewables-atlas.info/downloads/ [Accessed 22/05/2020]

5.5. Wind speed

The wind environment will dictate how much energy will be generated by turbines within the site. Turbines usually have a cut-in speed of ~3-4 m/s and function optimally at ~ 15 m/s. Cut-out speed is usually ~ 25 m/s to prevent damage during storms (The British Wind Generation Association, 2005). Wind speeds also determine whether it is safe to work on an offshore platform. Typically for work to be carried out on the exterior of an offshore platform the wind speed must be below 15 - 18 m/s (PAFA Consulting Engineers, 2001).

Sites with the highest average wind speed are those to the East of Scotland furthest offshore (Figure 12). YYY (12.41 m/s), YYYY (12.28 m/s), ZZ (12.16 m/s), ZZZ (12.16 m/s) and XXXX (11.45 m/s) have the highest average winter wind speeds (Figure 12). Sites with the lowest mean wind speed were those in more coastal areas such as XX (8.58 m/s), XXX (9.88 m/s) and XXXXX (10.65 m/s).

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Figure 12: Winter mean wind speed (m/s) 100 m above sea surface. Sites with the highest average wind speed are those in the east furthest away from the coast: YYY (12.41 m/s), YYYY (12.28 m/s), ZZ (12.16 m/s) and ZZZ (12.16 m/s). Sites in more sheltered coastal areas have the lowest

average wind speed: XX (8.58 m/s), XXX (9.88 m/s) and XXXXX (10.65 m/s). Data from: https://www.renewables-atlas.info/downloads/ [Accessed 22/05/2020].

Average summer wind speed showed the same pattern as winter wind speeds (Figure 13). Sites in the east furthest away from the coast had the highest average windspeeds: YYY (7.96 m/s), YYYY (7.87 m/s), ZZ (7.87 m/s), ZZZ (7.88 m/s) and XXXX (7.2 m/s). Sites in more sheltered coastal areas had slowest average wind speed: XX (5.69 m/s), XXX (6.07 m/s) and XXXXX (6.78 m/s)

Diagram removed

Figure 13: Summer mean wind speed (m/s) 100 m above sea surface. Average summer wind speed showed the same pattern as winter wind speeds (Figure 13). Sites in the east furthest away from the coast had the highest average windspeeds: YYY (7.96 m/s), YYYY (7.87 m/s), ZZ (7.87 m/s) and ZZZ (7.88 m/s). Sites in more sheltered coastal areas had slowest average wind speed: XX (5.69 m/s), XXX (6.07 m/s) and XXXXX (6.78 m/s). Data from: https://www.renewables-atlas.info/downloads/ [Accessed 22/05/2020].

5.6. Wave height

The wave environment of a site affects the hydrodynamic wave loading on both fixed and floating structures and can make offshore operations and maintenance dangerous. As a result, the wave environment is an important factor when making decisions regarding engineering of offshore structures and what sort of vessels will be required for accessing the site. Extreme hydrodynamic loads can cause severe stress and result in costly damage to the support structures of offshore infrastructure (Veldman *et al.*, 2011). Each site requires a specific safety case to ensure long-term operations vessels are suited to the environment. Working outside on offshore structures is usually stopped if waves heights are over 5.5m as this would be dangerous for recovery vessels if someone was to fall into the water (PAFA Consulting Engineers, 2001).

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XXXX has the highest average winter wave height (3.04m) while XX had the lowest (1.47m) (Figure 14). There was little variation between the other sites XXX (2.66m), YY (2.51 m) YYYY (2.99m), ZZ (2.24m) & ZZZ (2.40m).

Diagram removed

Figure 14: Average winter wave height. Site XXXX has the highest average wave height (3.0 m) while XX had the lowest (1.47 m). There is little variation in average wave height between the other sites XXX (2.66 m), YY (2.51m) YYYY (2.99m), ZZ (2.24m) & ZZZ (2.40m). Data from: https://www.renewables-atlas.info/downloads/ [Accessed 22/05/2020].

Summer average wave height followed a similar pattern. XX has the lowest average wave height (0.81m) (Figure 15). XXXXX also had a low average wave height of 0.99m. There was little variation between the other sites: XXX (1.39 m), XXXX (1.49m), YY (1.31m), YYY (1.52m), YYYY (1.50m), ZZ (1.21) & ZZZ (1.29m).

Diagram removed

Figure 15: Summer average wave height.

Summer average wave height followed a similar pattern. Site XX has the lowest average wave height (0.81m). XXXXX also had a low average wave height of 0.99m. There is little variation in wave height between the other sites: XXX (1.39 m), XXXX (1.49m), YY (1.31m), YYY (1.52m), YYYY (1.50m), ZZ (1.21) & ZZZ (1.29m). Data from: https://www.renewables-atlas.info/downloads/ [Accessed 22/05/2020].

5.7. Sea Surface Temperature

The temperature of sea water affects the seasonal growth of bivalves. In the UK bivalves grow when the water temperature reaches 8-9ºC. Fastest growth occurs during summer months at temperatures of 16-18ºC. Mussels are tolerant of low temperatures, while other bivalves such as clams and scallops are likely to die at temperatures below 5ºC (CEFAS, 2019). Maximum and minimum summer and winter temperatures are listed in Table 12.

Table 12: Minimum and maximum summer and winter temperatures of potential co-location sites. Data from: https://data.marine.gov.scot/dataset/annual-cycles-physical-chemical-and-biological-parameters-scottish-waters [Accessed 23/05/2020]

Site	Season	SST (°C)	
		Minimum	Maximum
XX	Winter	7.36	7.37
	Summer	11.96	11.99
XXX	Winter	7.74	7.88
	Summer	12.13	12.40

XXXX	Winter	7.39	7.58
	Summer	12.02	12.07
XXXXX	Winter	6.35	6.53
	Summer	11.40	11.38
YY	Winter	6.80	6.69
	Summer	11.68	11.68
YYY	Winter	7.01	7.18
	Summer	12.31	12.51
YYYY	Winter	7.14	7.29
	Summer	11.89	12.09
ZZ	Winter	6.13	6.28
	Summer	8.49	9.03
ZZZ	Winter	6.22	6.37
	Summer	12.16	12.34

Optimal temperature for mussel cultivation is between 8 and 17^{o}C (Table 8) however the species shows low levels of growth at -1^{o}C and can survive temperatures of -10^{o}C (CEFAS, 2019). All sites have temperatures lower the optimal range during winter – cultivation would be possible during winter months, but growth rate will be slower compared to warmer summer months.

5.8. Salinity

Water salinity affects the osmotic regulatory capacity of organisms by effecting the ability of living cells to take up water via osmosis. Mussels are a euryhaline species which means they are tolerant of fluctuations in salinity. However, a decline in salinity can result in a decreased growth rate and are less stressed under higher salinity conditions. This is because a decrease in salinity reduces the time that mussels open their valves which reduces feeding (CEFAS, 2019). Optimal salinity levels for mussel growth is 18 – 30 psu. Surface salinity at all sites is above the upper optimal limit of 30 psu (Table 13), however, mussels are tolerant of salinities up to 45 psu so all sites should be suitable (CEFAS, 2019).

Table 13: Minimum and maximum surface salinities of potential-colocation sites. Data from: https://data.marine.gov.scot/dataset/annual-cycles-physical-chemical-and-biological-parameters-scottish-waters [Accessed 23/05/2020]

Site	Surface Salinity (psu)	
	Minimum	Maximum
XX	33.6989	33.7888
	33.9814	34.0299
XXX	33.9265	34.1746
	34.2179	34.4305
XXXX	34.8488	34.9166
	34.8739	34.9451
XXXXX	34.5995	34.6839
	34.8819	34.9098
YY	34.8491	34.8908
	34.9128	34.9463
YYY	35.0813	35.1598
	35.0503	35.0929
YYYY	35.0675	35.1441
	35.0556	35.109
ZZ	34.679	34.7407
	34.5134	34.6347
ZZZ	34.7264	34.7851
	34.6567	34.7301

5.7. Dissolved oxygen

Seawater has an average dissolved oxygen concentration of ~ 8-11 mg/l. Dissolved oxygen concentration in water is influenced by a number of other environmental factors including water temperature, salinity, atmospheric pressure, water depth and biological activity. Higher temperatures lead to a decrease in dissolved oxygen concentration. Mussels are ‘poikilotherms’ which means their metabolic rate is mainly controlled by the temperature of the water they are in. An increase in temperature results in an increase in metabolic rate, which causes an increase in oxygen intake and growth rate. Optimal dissolved oxygen concentration for mussel cultivation is >7 mg/L (CEFAS, 2019).

Diagram removed

Figure 16: Dissolved oxygen concentration winter 2010. Data from: https://ec.europa.eu/maritimeaffairs/atlas/maritime_atlas/#lang=EN;p=w;bkgd=5;theme=122:0.75;c=-319969.47986156726,7946784.502895843;z=6 [Accessed: 07/07/2020].

Only dissolved oxygen data from winter was used as the summer data was focused on coastal areas which may not be representative of the offshore environment (Figure 16). Data for the west of Scotland was very limited, so dissolved oxygen concentration recorded for site XXX may be inaccurate. All sites were found to have a plentiful supply of dissolved oxygen ranging from 8.32 – 9.28 mg/L. However, dissolved oxygen concentration is likely to be lower during summer due to the increased water temperature.

5.8. Food availability

Mussels are filter feeds who obtain food by filtering it out of the water column. The rate at which mussels filter water is determined by water turbidity. Mussels main food source is phytoplankton (containing chlorophyll a), but they will also feed on organic detritus despite this being a poorer source of nutrition. Higher levels of water turbidity will cause the mussel to close its valve to avoid overloading of the intestinal space with inorganic particles that may be in the water column. Before reaching the upper threshold, mussels will expel undigested particles by excreting pseudofaeces. This reduces digestion and as a result reduces growth. Low water turbidity also results in a halt to water filtration as the effort required to digest the small amount of food available will exceed the energy obtained. Lab studies have shown that mussels start feeding when total particulate matter in the water column is between 0.5 and 1µg/L. The upper limit is thought to be dependent on the amount of chlorophyll a, organic matter and inorganic matter in the water column and self-regulated individual mussels according to their environment (CEFAS, 2019).

5.8.1. Chlorophyll a

Optimal chlorophyll a concentration for mussel growth is >6. CEFAS, (2019) states that sites with a chlorophyll concentration of <1 are not suitable for mussel cultivation which would make mussel cultivation infeasible in many sites especially during winter months (

Table *14*). However, Kapetsky, Aguilar-Manjarrez and Jenness, (2013) in their assessment of the feasibility of offshore mariculture report state that the lower threshold is <0.5 µg/L. Going by this lower threshold and looking at the maximum chlorophyll concentrations, cultivation at all sites is feasible.

Table 14: Minimum and maximum summer and winter chlorophyll concentrations at potential co-location sites. Data from: https://www.oceancolour.org/portal/ [Accessed 25/05/2020]

Site	Season	Chlorophyll concentration (µg/L)	
		Minimum	Maximum
XX	Winter	1.83	2.56
	Summer	0.95	1.24
XXX	Winter	0.6	1.45
	Summer	0.6	1.24
XXXX	Winter	0.39	0.59
	Summer	0.48	0.72
XXXXX	Winter	0.57	0.73
	Summer	0.49	0.65
YY	Winter	0.37	0.51
	Summer	0.38	0.64
YYY	Winter	0.3	0.41
	Summer	0.27	0.36
YYYY	Winter	0.3	0.4
	Summer	0.52	0.34
ZZ	Winter	0.54	1.03
	Summer	0.67	1.2
ZZZ	Winter	0.53	0.63
	Summer	1.1	1.33

5.8.2. Particulate organic matter (POM)

Particulate organic matter (POM) refers to the living organisms and non-living organic matter in the water column. In oceanic surface waters phytoplankton producers are usually present in higher quantities than non-living organic matter (Dong *et al.*, 2010). There is very little information regarding suspended POM concentration in the study area. Suspended POM concentration was based on (Eisma and Kalf, 1987) who reported concentrations of 0.3 mg/L (Figure 17). As no other recordings of suspended POM could be found this concentration was applied to all sites.

Diagram removed

Figure 17: Distribution of suspended particulate matter in the North Sea (Eisma and Kalf, 1987).

Although the offshore environment of the Northern North Sea has similar conditions throughout (Eisma and Kalf, 1987), it is likely this concentration is not representative of conditions to the West of Scotland (Sites XXX and XX). For future studies, it would be beneficial to investigate both more recent POM concentrations in the Northern North Sea, as well as concentrations in the west of Scotland.

5.8.3. Total particulate matter (TPM)

Total particulate matter (TPM) refers to all suspended particulate matter in the water column. Figure 18 shows a satellite derived annual mean surface TPM concentration for the period 1998-2015 (CEFAS, 2016).

Figure 18: Annual mean surface suspended particulate matter (SPM) concentration (mg/l) for the period 1998 – 2015 (CEFAS, 2016).

5.9. Multi-dimensional Scaling

Sites that are closer together have environmental conditions that are similar, while sites that appear further apart have conditions that differ (Figure 19). Sites that are geographically close together (e.g. XXXXX, YY and YYY) appear close together in the figure, while XX which in the west of Scotland in a sheltered coastal area appears far away as conditions in the sites are very different. A clear pattern can also be seen seasonally.

Diagram removed

Figure 19: Multi-dimensional scaling (MDS) analysis representing the relationship between environmental parameters and sites. Environmental data was normalised, and a resemblance matrix constructed based on Euclidean distance. Winter (blue triangles) and summer (red

triangles) conditions are shown. Sites that appear close together have similar environmental parameters, while sites that appear far apart have environmental parameters that differ.

6. Mussel production modelling

6.1. The FARM model

To analyse the potential of mussel cultivation at the study sites, the free-to-use, online shellfish modelling resource 'Farm Aquaculture Resource Management (FARM)' (http://www.farmscale.org) was used. The FARM model was created to aid farmers and managers by providing them with a simplified screening model to aid in determining a sustainable carrying capacity for potential farm sites. The model simulates cultivation considering advective water flow and how that transports relevant water properties through a cultivation set-up. The model has been designed to require a reduced set of environmental parameters compared to other models. Parameters required include water temperature, current speed, chlorophyll a concentration, POM concentration, TPM concentration and dissolved oxygen concentration (Ferreira, Hawkins and Bricker, 2007). The layout for the model is shown in figure 20.

Diagram removed

Figure 20: FARM model layout (Ferreira, Hawkins and Bricker, 2007).

The FARM model integrates physical and biogeochemical models, shellfish growth models and screening models to simulate cultivation. The general formula of the model is as follows:

$$\frac{\partial C}{\partial t} = -u\frac{\partial C}{\partial x} - w\frac{\partial C}{\partial z} + f\left(C, \sum_{i=1}^{i=m} n_i \gamma_i\right)$$

where:
c = concentration of resource (phytoplankton, POM, TPM),
t = time,
u = mean horizontal water velocity normal to farm cross-section,
x = farm section length,
w = fall velocity of suspended particles,
z = farm section depth,

m = number of weight classes in the population,
n_i = number of cultivated shellfish in weight class i,
y_i = growth functions for individual shellfish in weight class I,

A full description of the model can be found in Ferreira, Hawkins and Bricker, (2007). The model outputs used in this study are total harvestable biomass and total harvestable adults.

6.1.1. Co-location layout

A co-location site plan was drafted to determine the length and width of the site to be input into the FARM model. The co-location site has been based on Lagerveld, Röckmann and Scholl, (2014) '1,000x50,000 Cash Flow Farm'. Their conceptual site design consists of a 1,000 MW wind farm consisting of 5 clusters of wind turbines and 4 clusters of longlines between the 5 wind clusters capable of producing 50,000 tons of mussels per year. Mussel longlines and turbines are not connected in any way to minimise technical risks.

For the purpose of this study, 5 clusters of wind turbines (grey squares) and 4 clusters of longlines (white squares) have been integrated into one site (Figure 21). Each cluster has an area of 4 km^2. Each cluster of wind turbines has 5 turbines. Spacing between turbines is 1km based on industry standards (Personal Communication) and a 0.5 km safety zone is present between turbines and the outer edge of the turbine cluster (North SEE, no date).

The shellfish farm layout has been based on the current layout of Offshore Shellfish Ltd's site in which they have 16 longlines per km^2 (Personal Communication: John Holmyard, Offshore Shellfish Ltd). Each shellfish cluster has 2 rows of 16 longlines which leaves much more space between longlines compared to the industry standard of 3m (Seafish, 2005) ensuring there is plenty space for operations and management to be carried out in the offshore environment. This also allows space for future expansion which could be more mussel longlines or IMTA.

Shipping lanes (red lanes, Figure 21) have also been included in the conceptual design. Minimum required shipping lane size is determined using the equation 2L per ship, where L is 98.5% of the overall length of the largest ship operating in an area

(North SEE, no date). Dudgeon Offshore Wind Farm, (2014) states their contracted service operation vessel is 83.7 metres long – this was rounded up allowing for shipping lanes to be 200 m wide.

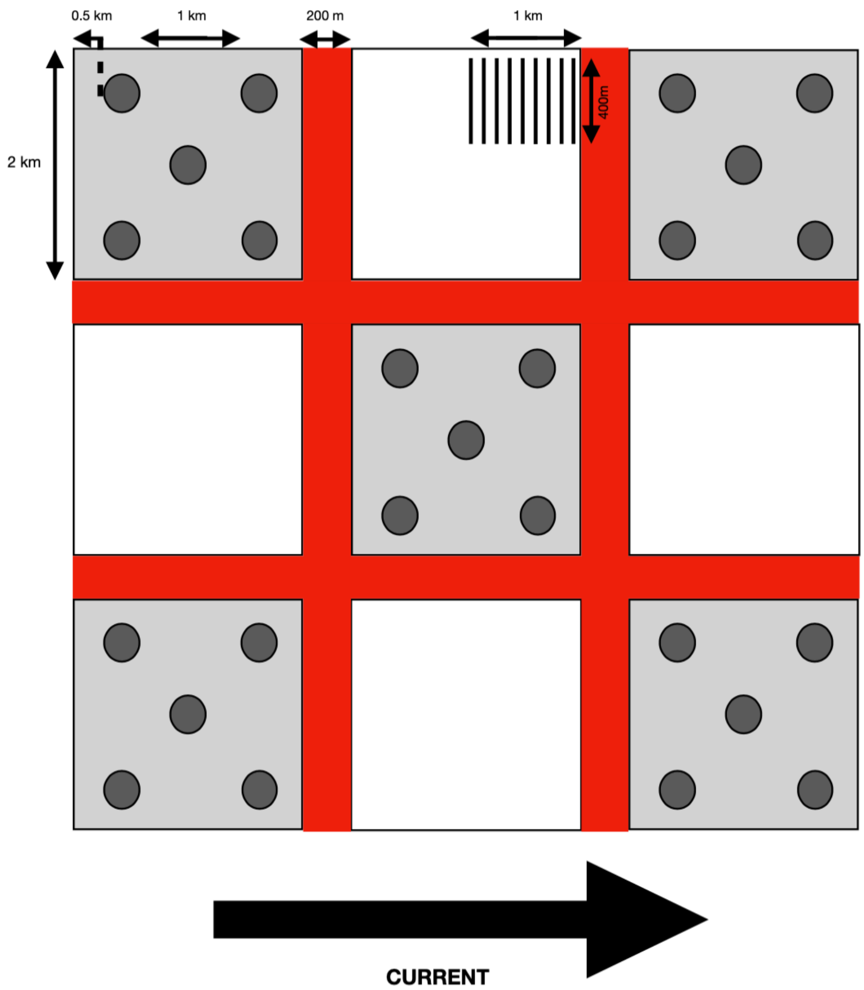

Figure 21: Conceptual design of co-located wind farm and mussel farm. Each square is 4 km^2. Grey squares represent wind turbine clusters. Dark grey circles represent wind turbines. Wind turbines have a 1km space between them, and a 0.5km safety zone is in place between turbines and the outer edge of the wind turbine clusters. White squares represent mussel cultivation clusters and black solid lines represent longlines. Mussel cultivation clusters have 16 longlines per km^2 – two rows of 16 longlines per cluster. Red represents shipping lanes which have a width of 200 m to allow for operations vessels. Direction of the ocean current relative to the mussel longlines is shown at the bottom of the diagram.

Commented [KM33]: Good use of figure and also excellent legend which means figure can 'stand on its own'

This gives the conceptual site a total area of 40.96 km^2. For the purpose the FARM model, farm width was set to 400m, and farm length to 1000m and number of sections was set to 8. The farm depth was set to 6m, and cultivation period was set to 548 days (Seafish, 2005). Each site was tested with a range of stocking densities to establish the optimal density for each site. Stocking densities tested were 150, 250, 500, 600, 700, 800, 900 and 950 individuals/m^3. The model doesn't allow for densities above 999 individuals/m^3 to be tested. Table 15 lists all inputs used.

6.1.2. Environmental parameters

As the FARM model only allows for single values for environmental parameters to be input in some cases averages had to be used. A full list of environmental parameter values used is listed in Table 15.

6.1.3. Model outputs

The FARM model outputs used for this study were total harvestable biomass (tons) and total harvestable adults (number of individuals). Total harvestable biomass (tons) and total harvestable adults (number of individuals) were multiplied by 2 to give the yield of 16 longlines/km^2. This was done instead of running a model with height and width of 1000m and 16 sections as this large a site made the model run very slowly and at times not producing an output at all.

Yield per metre of longline was calculated using the following formula:

(Yield per km^2/16)/400

Based on their being 16 longlines per km^2 and each longline being 400m long.

Percentage of initial crop that was harvestable after the cultivation period of 548 days was calculated using the following formula:

(Total harvestable adults (individuals) / initial number of individuals) x 100

Total harvestable biomass per km^2 was converted from tons to kg by multiplying the biomass by 1000. The value of the crop was calculated using a UK average price of £1 per kg (Personal communication: xxxxxxxxxx). This value was then multiplied by 16 so the potential revenue generated from $16km^2$ of mussel cultivation (as per the conceptual co-location design: Figure 21).

6.1.4. Statistical Analysis

All statistical analysis was conducted with R software (version 3.3.2, R Core team (2016)).

The harvestable biomass (binary dependent variable) was analysed by logistic regression using a general linear model relative to the model terms 'Stocking density' (continuous independent variable) and 'Site' (independent nominal variable with nine levels: XX, XXX, XXXX, XXXXX, YY, YYY, YYYY, ZZ & ZZZ). The relationship between site and stocking density was compared using site ZZ as the baseline.

The percentage of initial crop harvestable after 548 days (binary dependent variable) was analysed by logistic regression using a general linear model relative to the model terms 'Stocking density' (continuous independent variable) and 'Site' (independent nominal variable with nine levels: XX, XXX, XXXX, XXXXX, YY, YYY, YYYY, ZZ & ZZZ). The relationship between site and percentage of initial crop harvestable after 548 days was compared using site ZZ as the baseline.

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Table 15: Inputs used for FARM model

Commented [KM35]: When using a model as part of a study it is critical to list the input data, this might be reported in the body of the dissertation, as here, or might form an appendix or supplementary materials.

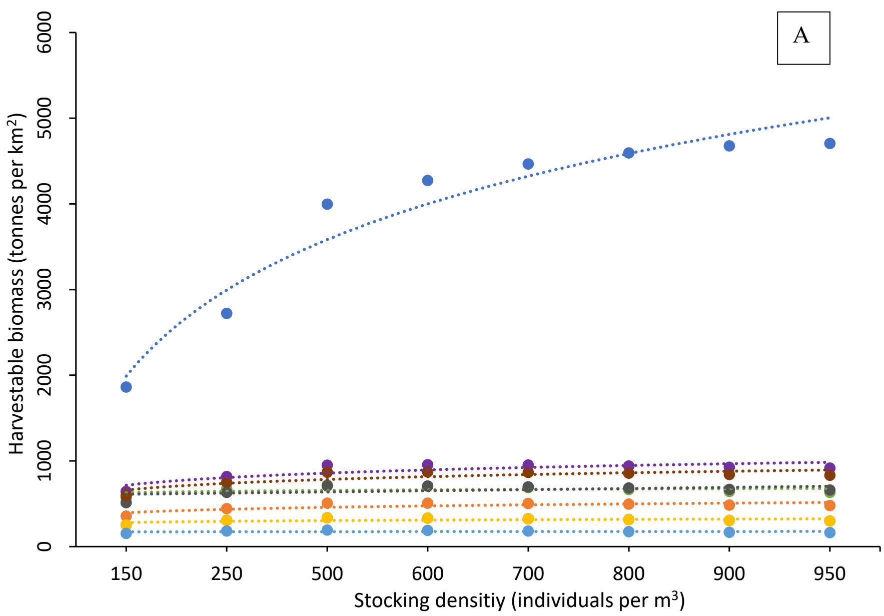
SITE	Water Temp (°C)	Current Speed (m/s)	Chlorophyll a (ug/L)	POM (mg/L)	TPM (mg/L)	Dissolved Oxygen (mg/L)	Farm Width (m)	Farm Length (m)	Farm Depth (m)	Cultivation period (days)
XX	9.67	1.12	1.65	0.30	4.60	9.28	400	1000	6	548
XXX	10.04	0.46	0.97	0.30	4.60	9.28	400	1000	6	548
XXXX	9.76	0.40	0.55	0.30	0.70	8.32	400	1000	6	548
XXXXX	8.92	0.27	0.61	0.30	0.80	8.32	400	1000	6	548
YY	9.21	0.31	0.48	0.30	0.80	9.28	400	1000	6	548
YYY	9.75	0.24	0.34	0.30	0.80	8.32	400	1000	6	548
YYYY	9.60	0.29	1.29	0.30	0.80	9.28	400	1000	6	548
ZZ	7.48	0.39	0.86	0.30	0.80	8.32	400	1000	6	548
ZZZ	9.27	0.45	0.90	0.30	0.80	8.32	400	1000	6	548
Notes	Average of summer & winter temp.	Average of mean & neap tide current.	Average of winter & summer conc.		Annual Surface suspended particulate matter.	Winter data only - summer data didn't cover far enough away from coastal waters.	Based on co-location farm layout	Based on co-location farm layout	(Seafish, 2005)	(Seafish, 2005)

6.2. Results

6.2.1. Harvestable biomass

Site XX had the highest harvestable biomass (tons per km^2) at all stocking densities tested compared to the other 8 sites (Figure 22). The harvestable biomass of XX increased continually as stocking density increased. Site YYY had the lowest harvestable biomass at all stocking densities tested. Harvestable biomass increased continually from 150 – 500 individuals per m^3 but started to decrease as stocking density increased after this point. All other sites followed this trend with harvestable biomass peaking at different stocking densities. Sites XXX and ZZZ peaked at 600 individuals per m^3 while sites XXXX, XXXXX, YY, YYY, YYYY and ZZ peaked at 500 individuals per m^3.

Site names – legends removed



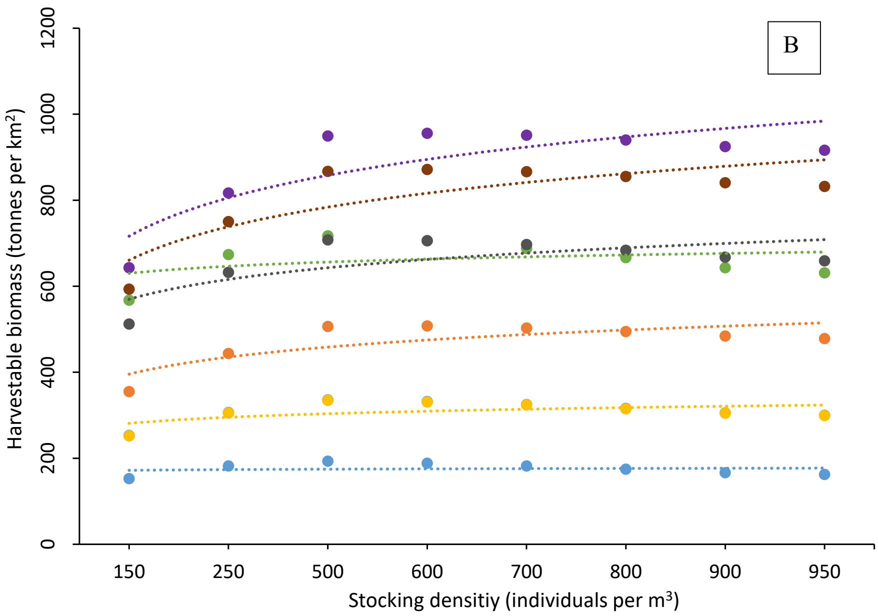


Figure 22 (A): Predicted harvestable biomass (tons per km^2) at study sites (XX, XXX, XXXX, XXXXX, YY, YYY, YYYY, ZZ and ZZZ) at different stocking densities at the end of the cultivation period (548 days). Based on 16 longlines in a km^2. (B) As before with XX removed for the purpose of clarity.

Stocking density was found to have a significant effect on harvestable biomass (Table 16). XX was the only site where a significant relationship between site and harvestable biomass was found.

Table 16: General linear model output. Stocking density was found to have a significant effect on harvestable biomass. The relationship between site and stocking density was compared using site ZZ as the baseline. XX was the only site where a significant relationship between site and harvestable biomass was found.

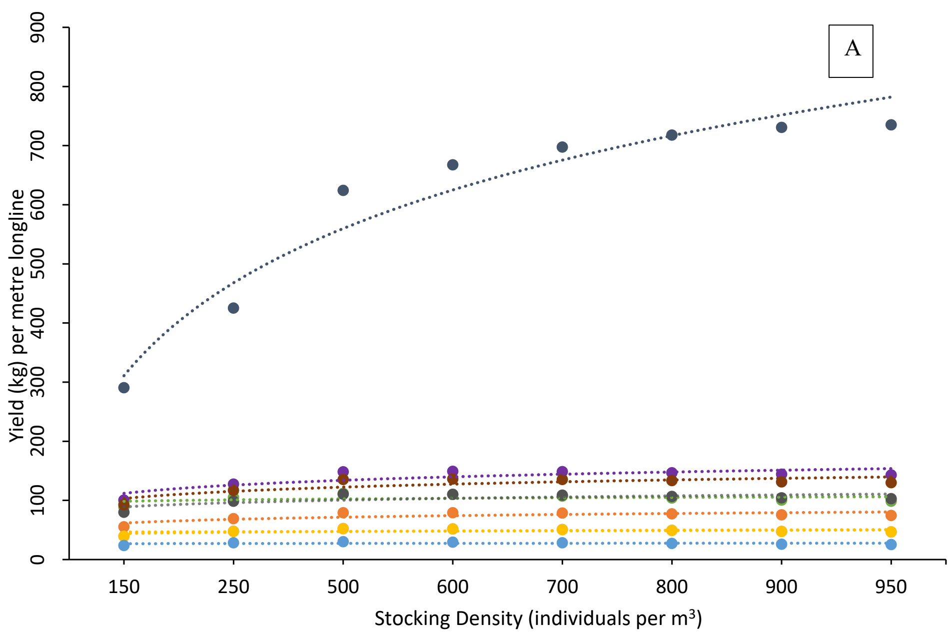
Commented [KM36]: It is very important to report full outputs from the statistical models, but it is important to present the information clearly, as here, rather than just cutting and pasting from the rather clunky software package outputs that are typical of software packages.

Site	**Estimate**	**Std. error**	**t-value**	**p-value**
Intercept	588.58	266.35	2.21	0.03
Stocking density	0.12	0.39	0.31	0.76
XX	1531.47	294.41	5.20	>0.0001
XXX	0.13	0.52	0.24	0.81
XXXX	44.46	405.75	0.11	0.91
XXXXX	-296.71	466.54	-0.64	0.53

YY	-298.05	467.16	-0.64	0.53
YYY	-410.53	565.64	-0.73	0.47
YYYY	60.84	371.08	0.16	0.87
ZZZ	95.66	361.40	0.27	0.79

6.2.2. Yield per metre longline

Yield per metre longline increased continually for site XX at all stocking densities tested (Figure 23). Site YYY had the lowest yield per metre at all stocking densities tested. Yield per metre longline increased continually from 150 – 500 individuals per m^3 but started to decrease as stocking density increased after this point. All other sites followed this trend with yield peaking at different stocking densities. Sites XXX and ZZZ peaked at 600 individuals per m^3 while sites XXXX, XXXXX, YY, YYY, YYYY and ZZ peaked at 500 individuals per m^3.



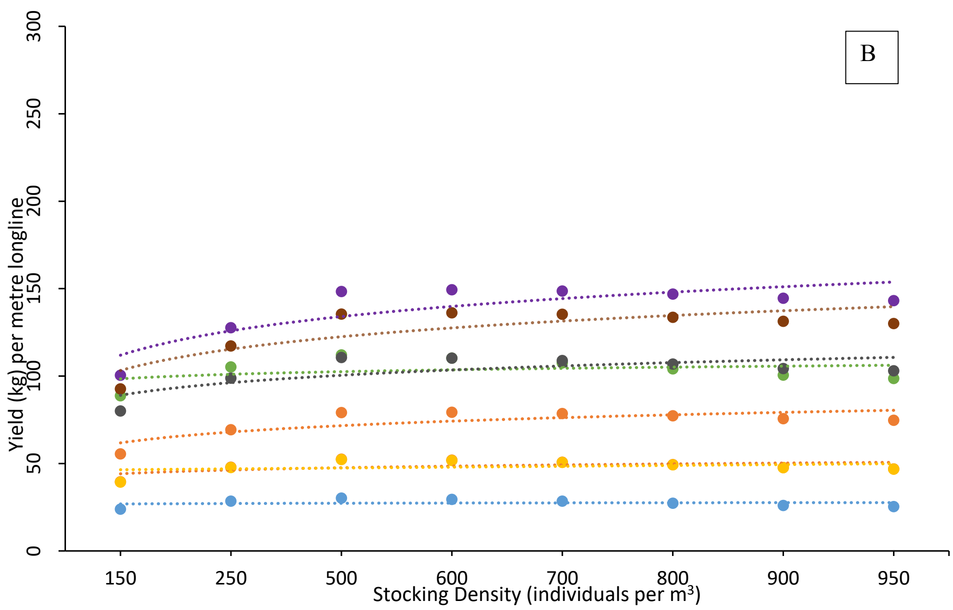
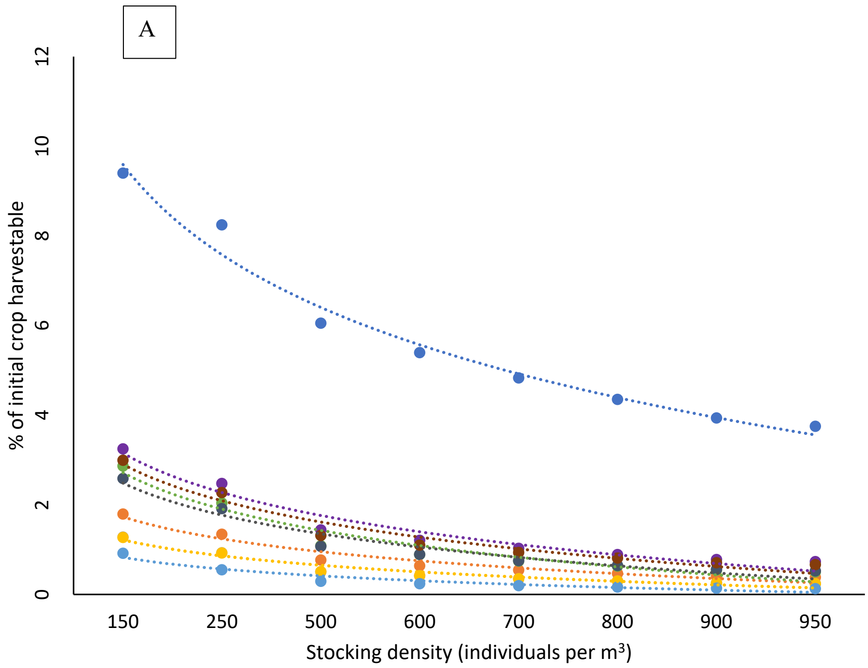


Figure 23: (A): Predicted yield per metre of longline at study sites (XX, XXX, XXXX, XXXXX, YY, YYY, YYYY, ZZ and ZZZ) at different stocking densities at the end of the cultivation period (548 days). Based on 16 longlines in a km^2. (B) As before with XX removed for the purpose of clarity.

6.2.3. Harvestable individuals

The percentage of initial crop harvestable after 548 days continually decreased as stocking density increased at all sites (Figure 24). Site XX had the highest percentage of initial crop harvestable after 548 days at all stocking densities tested compared to the other 8 sites while YYY had the lowest.



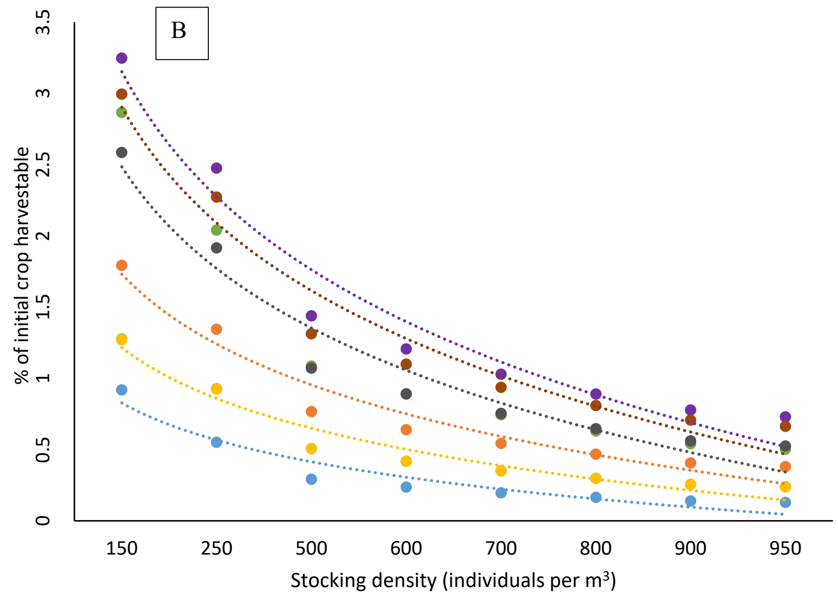


Figure 24 (A): Predicted percentage of initial crop harvestable at the end of the cultivation period (548 days) at study sites (XX, XXX, XXXX, XXXXX, YY, YYY, YYYY, ZZ and ZZZ) at different stocking densities (150, 250, 500, 600, 700, 800, 900 and 950). (B): As before with XX removed for the purpose of clarity.

Stocking density was found to have a significant effect on percentage of initial crop harvestable at the end of the cultivation period (548 days) (Table 17). The relationship between site and stocking density was compared using site ZZ as the baseline. The relationship between site and percentage of crop harvestable was significant for sites XX, XXX, XXXX, XXXXX, YY and YYY.

Table 17: General linear model output. Stocking density was found to have a significant effect on percentage of initial crop harvestable at the end of the cultivation period (548 days). The relationship between site and stocking density was compared using site ZZ as the baseline. The relationship between site and percentage of crop harvestable was significant for sites XX, XXX, XXXX, XXXXX, YY and YYY.

Site	Estimate	Std. error	t-value	p-value
Intercept	2.77	0.24	11.36	>0.0001
Stocking density	-0.003	0.0005	-5.92	>0.0001
XX	7.37	0.27	27.11	>0.0001
XXX	0.71	0.33	2.19	>0.05
XXXX	-0.85	0.38	-2.23	>0.05
XXXXX	-1.38	0.44	-3.14	>0.001
YY	-1.38	0.44	-3.16	>0.001
YYY	-1.81	0.50	-3.65	>0.0001
YYYY	0.30	0.34	0.88	0.38
ZZZ	0.44	0.33	1.33	0.19

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6.3. Discussion

Potential yield varied between sites. Sites to the ssss of Scotland had the highest potential yields. Site XX has the highest chlorophyll a concentration and highest current speed, and as a result the highest potential yield of mussels (Figure 22). XX also had the highest % of crop that reached market size at the end of the cultivation period at all stocking densities tested (Figure 24). XXX had the second highest potential yield and % of crop that reached market size and the highest average temperature, second highest current speed and third highest chlorophyll a concentration.

Commented [KM37]: Nice discussion that puts the results in context with other studies, well referenced to the primary literature. Good structure to the discussion, thinking about the results, the explanation for them, and caveats that might lead to alternative explanations.

Sites to the tttt of Scotland showed lower potential yields. YYY and YY had the lowest and second lowest potential yields (Figure 22). These two sites also had the lowest % of initial crop that reached market size at all densities tested (Figure 24). Both sites had low chlorophyll a concentration and low current speed which reduces production capacity. YYYY also had a low current speed but had a much greater chlorophyll concentration and as a result a greater potential yield and % of crop that reached market size despite being geographically very close to sites YYY & YY. Sites ZZ and ZZZ also showed variance in potential yield despite being close together – both sites have similar current speed and chlorophyll a concentration, but ZZ has an average temperature of 7.48^{o}C while ZZZ has an average of 9.27^{o}C and as a result will have a higher growth rate.

Sites in the ssss of Scotland (XX & XXX) are in more sheltered coastal areas compared to other sites, which although beneficial logistically, means they have less space for expansion. Being closer to the coast also means sites in the ssss are more likely to be affected by anthropogenic pollution (Silva *et al.*, 2011). These sites also have the lowest average wind speeds, meaning they have the lowest potential for wind energy generation. Sites to the north (XXXX) and ssss (XXXXX, YY, YYY, YYYY, ZZ & ZZZ) are further into the offshore environment compared to those to the ssss of Scotland, and as a result have more space for expansion and are likely to have better water quality (Silva *et al.*, 2011). These sites also have higher average wind speeds, making them potentially more attractive for offshore wind development, however they have lower productivity for mussel cultivation. The increased distance from the shore also is less beneficial logistically.

XX showed a continually increasing yield at all stocking densities tested, while XXX peaked at 700 individuals per m^3. XXXX peaked at 500 individuals per m^3. All sites in the tttt showed the greatest potential yield at 500 individuals per m^3 apart from ZZZ, which peaked at 600 individuals per m^3. Increasing mussel density is known to decrease mussel yield as high stocking densities increases the number of mussels dislodged from grow-out ropes and subsequently lost. Knowing the optimal stocking density is beneficial for a number of reasons. High stocking densities can also result in larger mussels out competing smaller mussels, resulting in more dislodged mussels from competition for space or a reduced growth rate due to competition for resources (Karayücel *et al.*, 2015).

Two paragraphs removed.

6.3.1. Limitations

The optimal stocking densities reported may not be representative of the carrying capacity of the area. 'Carrying capacity' is the maximum volume of mussels that can be cultivated without causing any negative repercussions to the ecosystem. The introduction of a mussel farm will result in changes in the available food in the area – this may be in terms of volume, species composition of plankton or a combination of both – which can have a negative effect on wild species in the area who also rely on this food source (Lagerveld, Röckmann and Scholl, 2014). Similarly, biofouling was not considered in this study. Biofouling on grow-out ropes can reduce mussel growth and quality with sites in Canada reporting up to 50% mortality of cultivated mussels due to heavy biofouling (Kamermans and Capelle, 2018). An understanding of the wild species and the energy dynamics within the area would help to understand the interactions between the environment and a potential mussel farm.

Commented [KM38]: Good to have an honest reflection on what the limitations of the study might be. This shows the ability to self-evaluate and self-criticise.

These predicted yields are based on conditions within the sites without the addition of offshore infrastructure. The introduction of wind turbines and mussel cultivation related infrastructure may result in the hydrodynamics of the area being altered, and thus affect how food travels through the water column (Rosland *et al.*, 2011). This may lead to more or less food being available for mussels being cultivated and wild species in the area (Rivier *et al.*, 2016).

The models were also run using some values that were potentially unrepresentative of all sites, for example, the TPM value used was taken from a study on the North Sea and this value was used for all sites as no other source could be found. However, this source is dated and may not represent current conditions, and as it is based in the North Sea it is unlikely to be accurate for sites to the ssss of Scotland (XX & XXX). Seasonal fluctuations in growth rate were also not considered. The FARM model only allows for one value to be input for each environmental parameter. As a result, fluctuations in growth rate are not considered – an important consideration in the offshore environment which is often nutrient limited compared to coastal and nearshore sites (Langan, 2013).

This study also did not consider which sites are most effected by extreme weather events. Conditions in the North Sea are known to be extreme, with wave heights of up to 12 m (Jansen *et al.*, 2016). It would be beneficial to know how often extreme weather events occur, the duration of such events and the severity as these will affect how feasible co-location is at the site as well as engineering decisions regarding infrastructure. Also not considered is the frequency and duration of harmful algal blooms in Scottish waters. This is essential to ensure sites that are selected will produce mussels that are safe for human consumption (Langan, 2013) particularly in sites to the ssss of Scotland which is an area associated with blooms of *Karenia mikimotoi* (MCCIP, 2020).

7. Future research

Future research would benefit from focusing on developing an understanding of interactions between offshore mussel farms and the environment. Future productivity modelling would also benefit from considering seasonal fluctuations in environmental conditions as these effect growth rate throughout the cultivation period. Future models would also benefit from investigating the hydrodynamic effects of placing a mussel farm within a wind farm site as this may farm conditions. This would allow for more dynamic modelling to take place, thus improving carrying capacity optimisation and predicted productivity results. A better understanding of energy dynamics and environmental interactions would also be beneficial for future integrated multitrophic aquaculture projects which could further improve the sustainability of aquaculture.

Commented [KM39]: Good to show some horizon scanning to demonstrate that you are really thinking about the issues.

Understanding the legislation surrounding offshore co-location in Scottish waters is an important consideration moving forward, as is interviewing specialists, potential stakeholders and the public. This can allow for industry knowledge and local knowledge to be integrated to produce optimal new developments.

8. Conclusion

Offshore co-location offers a solution for sustainably using marine space as competition between users continues to grow. Placing aquaculture sites within offshore windfarms means the large spatial requirements of offshore wind can be utilised for food production and overexploited coastal areas can be avoided. This can potentially reduce conflicts between sea users by providing a more stable yield compared to fishing to mitigate against lost fishing grounds.

Commented [KM40]: Good to wrap up the discussion with the key points.

The sector is still very much in its infancy, and finfish cultivation is still in the pre-commercial research and design phase, however, offshore mussel cultivation has the potential to be a fruitful endeavour. Mussels are a good potential candidate for offshore co-location as they require minimal husbandry and no additional inputs. Going forward, efforts should be focused on understanding interactions between integrated mussel and wind offshore sites and the environment to improve optimal carrying capacities recommendations.

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