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Identification of areas of aquaculture potential in English waters (MMO 1184)

MMO1184: Identification of areas of aquaculture potential in English waters

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Executive Summary

Regulatory barriers and availability of new production sites are limiting factors for growth in the UK aquaculture sector. In England, industry challenges could be reduced by enabling the sustainable use of sites that are most suitable for aquaculture, streamlining regulatory and licensing procedures and improving policy. To address these barriers through marine spatial planning the Marine Management Organisation (MMO) commissioned development of spatial models to spatially delineate areas that have potential for aquaculture development in the South and East Coast Marine Plan Areas (MMO1040).

With this project, the MMO commissioned Cefas to undertake an aquaculture potential mapping study. The overall objective of this work is to delineate areas of potential for aquaculture development in English waters (out to the median line with other countries or the full extent of the EEZ as appropriate) up to the Economic Exclusion Zone (EEZ)) by: 1) identifying the spatial extent viable for growth (environmental constraints) of current and emerging species of importance to aquaculture in England, in coastal and offshore waters; 2) identifying the current technical constraints for site identification resulting from aquaculture techniques used for culture of species of interest.

Suitable areas (‘zones’) for aquaculture of 14 species off the English coast were determined using a Geographic Information System (GIS) based approach. The species selected for study were 4 seaweed species - *Saccharina latissima* (sugar kelp), *Laminaria digitata* (oarweed), *Alaria esculenta* (winged kelp) and *Palmaria palmata* (dulse); 4 finfish species - *Salmo salar* (Atlantic salmon), *Oncorhynchus mykiss* (rainbow trout), *Salmo trutta trutta* (sea trout) and *Gadus morhua* (Atlantic cod); 1 crustacean species; *Homarus gammarus* (European lobster); and 5 bivalve mollusc species - *Crassostrea gigas* (Pacific oyster), *Ostrea edulis* (native oyster), *Mytilus edulis* (blue mussel)*, Ruditapes philippinarum* (Manila clam) and *Pecten maximus* (King scallop).

The key environmental layers that were considered to inform species distributions include: sea surface temperature, salinity, light climate, total oxidized nitrogen, dissolved oxygen and chlorophyll concentration. Current speed, peak wave height, bottom substrate and bathymetry where considered under the technical constraints, as they mainly provide constraints on the aquaculture infrastructure (rather than the organisms when farmed).

Environmental variables were classified in optimal, suboptimal and unsuitable ranges for each of the species investigated, based on published literature. Comparison of these threshold levels with spatial data provided a suitability map showing the sites where the species can survive or thrive. In addition, technical constraints on the different mechanisms of aquaculture of these 14 species were extracted from the published literature.

The result of this study showed that waters off England present suitable areas for growth and farming of the 14 species investigated. Particularly, the kelps *S. latissima* and *L. digitata*, sea trout, lobster, oysters (*Crassostrea gigas* and *Ostrea edulis*) and

blue mussel appeared the most suitable species for aquaculture, based on their environmental ranges for optimal/suboptimal growth. Rainbow trout and Atlantic salmon showed suitability across most English waters but were best suited to more northerly regions. This was especially so for Atlantic salmon which showed a high level of suitability off the north west coast of England. Manila clam showed a mixed picture, with reasonably high levels of suitability in the English Channel and Celtic Sea and some coastal areas of the north east. However, large areas off the north west and east coast of England were deemed unsuitable for aquaculture due to the minimum sea surface temperature being lower than that suitable for the clam.

Farming of *Alaria esculenta* and Atlantic cod appeared to be limited environmental factors (e.g. too high sea surface temperature occurring in summer in parts of the English waters). Similarly, cultivation of King scallop was limited to the south and south west regions because the minimum temperature for this species is below that experienced elsewhere in English waters.

Following completion of the study the following recommendations are made:

- identified suitable regions with this study should be followed up with individual localised investigations. Such investigations would use data layers with an increased resolution to enable more precise siting of aquaculture and consider the site-specific nature of the seabed substrate, the depth of water and other potentially relevant environmental layers such as concentration of Suspended Particulate Matter (both organic and inorganic forms).
- data layers used in this report should be kept up to date as additional data becomes available. This is recommended for both the environmental and technical data layers used in this study.
- a gap in understanding of the effect of wave heights on aquaculture systems should be filled by developing hydrodynamic models to understand the impact of wave height on specific aquaculture systems. Such models could be validated using laboratory or in situ experiments.
- as the aquaculture industry moves towards Integrated Multi-trophic Aquaculture (IMTA) it is recommended that the current study is progressed to highlight the possibility of combining aquaculture of species belonging to different trophic levels.

The output of this study will be combined with other information by the Marine Management Organisation (MMO), such as marine activities distributions and intensities, vessel routing schemes etc., to identify the most suitable locations for farming (i.e. optimizing the farm yield, while reducing potential conflicts with other uses or activities in the marine area). It is advised that sites of interest should be investigated at higher detail and resolution than carried out in this study (which aimed only to provide a wider and strategic view of aquaculture suitability for waters off England).

1 Introduction

Regulatory barriers and availability of new production sites are limiting factors for growth in the UK aquaculture sector. In England, industry challenges could be reduced by enabling the sustainable use of sites that are most suitable for aquaculture, streamlining regulatory and licensing procedures and improving policy.

To address these barriers through marine planning the Marine Management Organisation (MMO) commissioned development of spatial models to spatially delineate areas that have potential for aquaculture development in the South and East Inshore and Offshore Marine Plan Areas (MMO1040). As the development of marine plan has continued, the MMO is seeking to develop equivalent models with greater spatial extent to encompass the North East, North West, South East and South West Inshore and Offshore Marine Plan Areas.

With this project, the MMO commissioned Cefas to undertake an aquaculture potential mapping study. The project is administered under the Cefas/MMO partnership agreement Service Level Agreement (SLA) 3. The overall objective of this work is to delineate areas of potential for aquaculture development in English waters (up to the limit of the EEZ or median line) by:

1. identifying the spatial extent viable for growth (environmental constraints) of current and emerging species of importance to aquaculture in England, in coastal and offshore waters
2. identifying the current technical constraints (hard and soft) for site identification resulting from aquaculture techniques used for culture of species of interest e.g. bathymetric limits for seabed culture techniques.

Suitable areas (‘zones’) for aquaculture of 14 species off the English coast were determined using a Geographic Information System (GIS)-based approach. Environmental variables were classified in optimal, suboptimal and unsuitable ranges for each of the species investigated based on published literature. Comparison of these threshold levels with spatial data provided a suitability map showing the sites where the species can survive or thrive. In addition, technical constraints on the different mechanisms of aquaculture of these 14 species were extracted from the published literature. These are presented in this report along with the GIS layers. This report follows a similar process to that identified in a previous report on identification of sites for seaweed farming in English waters (Capuzzo *et al.*, 2018).

The key environmental layers that were considered include: sea surface temperature, salinity, light climate, total oxidized nitrogen, dissolved oxygen and chlorophyll concentration. These layers were combined in ‘suitability’ layers. Current speed, peak wave height, bottom substrate and bathymetry where considered under the technical constraints; these layers were not combined in the ‘suitability’ maps as they mainly provide constraints on the infrastructure (rather than the organisms farmed), but recommended threshold values were provided.

Species assessed in this study include:

- Seaweed Species
    - *Saccharina latissima* (sugar kelp)
    - *Laminaria digitata* (oarweed)
    - *Alaria esculenta* (winged kelp)
    - *Palmaria palmata* (dulse)
- Finfish Species
    - *Salmo salar* (Atlantic salmon)
    - *Oncorhynchus mykiss* (rainbow trout)
    - *Salmo trutta trutta* (brown (sea) trout)
    - *Gadus morhua* (Atlantic cod)
- Crustacean Species
    - *Homarus gammarus* (European lobster)
- Bivalve mollusc Species
    - *Crassostrea gigas* (Pacific oyster)
    - *Ostrea edulis* (native (flat) oyster)
    - *Mytilus edulis* (blue mussel)
    - *Ruditapes philippinarum* (Manila clam)
    - *Pecten maximus* (king scallop).

The following limitations were set on the work: based on the available data, resolution of the data layers was of approximately 3-4 km. Consequently, estuaries and transitional areas were not resolved in the suitability maps and technical constrains layers. The study is limited to national jurisdiction waters although data values in certain offshore areas (see Methods section) had a lower confidence level due to lack of available in situ measurements.

1.1 Aquaculture in the UK

In 2010 a review on global food security was published in the journal Science (Godfray *et al.*, 2010) and a global strategy was presented to develop a sustainable and equitable food delivery model. One of the key recommendations was the expansion of the aquaculture sector. Potential for aquaculture growth has been highlighted in a recent report from Seafish (Hambrey and Evans, 2016).

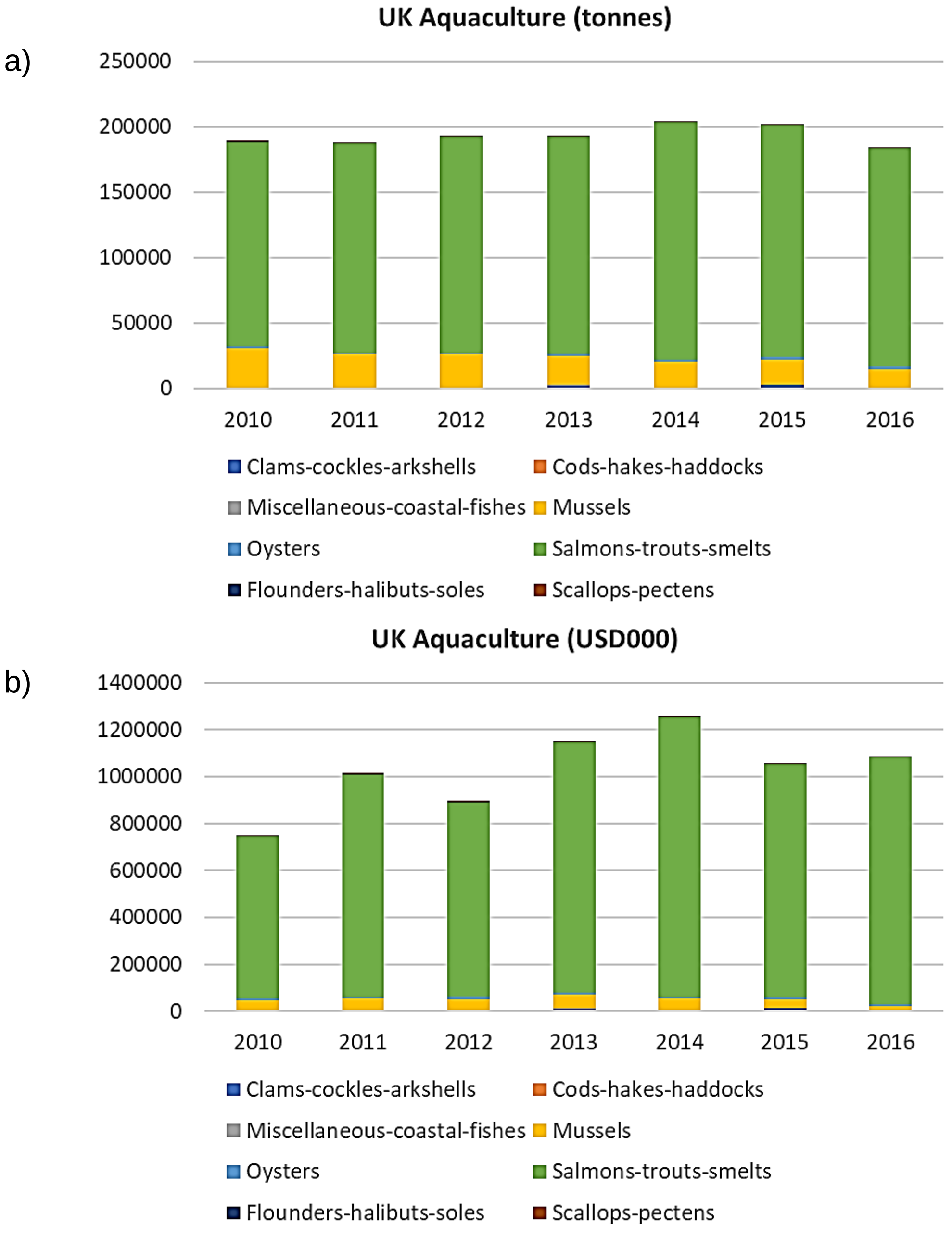
Estimates of aquaculture production for the UK are available through the FAO website (www.fao.org/fishery/statistics/global-aquaculture-production/en). When looking at the aquaculture production (both in terms of weight (tonnes) and as value (USD$ (000s)), between 2010 and 2016, it is evident that the category ‘Salmon-trouts-smelts’ dominated production (accounting for 87% of the production in weight and 94% of the production as value; Figure 1). Within this category, Atlantic salmon (*Salmo salar*) represented approximately 99% of production (both in weight and value), with Rainbow trout (*Oncorhynchus mykiss*) accounting for the majority of the remaining 1%.

The second most important category in UK aquaculture is ‘Mussels’ and particularly blue mussel (*Mytilus edulis*), which represented on average (between 2010-2016) 12% of the total UK production in weight, and 4% of production in value (Figure 1).

The remaining 1% of UK aquaculture production is represented by ‘Oysters’, with Pacific oyster (*Crassostrea gigas*) accounting for almost all the production.

It is important to note that these estimates include only farmed species (i.e. species collected/harvested from the wild are not included) and there are no available estimates of seaweed production for the UK (see Section 1.1.1 for further details on seaweed).

Figure 1: Cumulative annual aquaculture production in the UK a) by weight in tonnes and b) by value (USD$ (000s)) (from FAO, 2019, downloaded on 20/03/2019).



1.1.1 Seaweed aquaculture potential in Europe and the UK

There is an increasing interest at both the global and national level in seaweed (or macroalgae) production. Global aquatic plant production (from aquaculture and harvest of wild resources) has now exceeded 30 million tonnes per year, almost all of which (96%) has been produced from aquaculture sources (FAO, 2018a). Particularly, production has tripled between 2000 and 2016 growing continuously with average yearly increments of 7% (FAO, 2018a).

Although the seaweed market is dominated by Asian countries (e.g. China, Indonesia, Philippines and South Korea), interest in seaweed production is increasing in Europe and in the UK.

The high demand for seaweeds has been driven by their multiple applications and uses: for human consumption or for flavouring; for production of phycocolloids (e.g. carrageenan, alginate, agar), for animal feed, fertilizers, probiotics, pharmaceutical and cosmetics and for water remediation (West *et al.*, 2016). More recently, research projects have been investigating feasibility of using seaweed biomass as a source for third generation biofuel production (see for example SeaGas project, http://seagas.co.uk/, or MacroFuels, https://www.macrofuels.eu/).

In the UK, seaweeds have traditionally been used for centuries for food, feed and fertilizers. Demand has so far been met by harvesting of wild resources; however, the increase in demand of seaweed biomass is likely going to be met by farming rather than natural harvest (see review by Capuzzo and McKie, 2016). The UK has an extensive coastline offering suitable environmental conditions for seaweed growth, however factors such as lack of information on operational costs, biomass yields and ecological effects, as well as unclear regulatory context, are perceived to limit the development of this young industry (Capuzzo and McKie, 2016; Wood *et al.*, 2017).

Seaweed production from countries in the European continent is mainly from harvest of wild resources (Capuzzo and McKie, 2016). Capuzzo *et al.*, (2018) provides a detailed analysis of seaweed production by European countries. In them, the most commonly farmed species by EU country is *Saccharina latissima* (sugar kelp, brown seaweed), in Denmark, Norway and Spain; *Alaria esculenta* (dabberlocks or wing kelp, brown seaweed) in Ireland and Norway; and *Gracilaria* spp. in the warmer waters of Italy and Spain. Some European countries also farm unspecified red, brown or green seaweeds.

There are no records of seaweed production for the UK in the FAO database although seaweeds are harvested in various parts of the UK (see review by Capuzzo and McKie, 2016). For example, approximately 5,000 tonnes per year of *Ascophyllum nodosum* were harvested in Scotland, while *Porphyra* (laver or nori) species is harvested in Wales (James, 2010). Other species harvested in the UK and available as dry, fresh or condiments via local companies are *Palmaria palmata* (dulse), *Laminaria digitata* (oarweed or Atlantic kombu), *Chondrus crispus* (Irish moss), *Himanthalia elongata* (sea spaghetti or thongweed), and *Ulva* (sea lettuce).

Aquaculture production of seaweed farming industry in the UK is still limited although there are established pilot farms for research and development in Scotland (Scottish

Association of Marine Science), Northern Ireland (Queen's University, Belfast), the Shetlands (University of the Highlands and Islands) and Wales (Swansea University), and a few commercial farms (e.g. Rathlin Kelp, on Rathlin Island, and recent applications for development of seaweed farms on the south and east coast of England). Seaweed species farmed in the UK include: *Saccharina latissima*, *Laminaria digitata*, *Alaria esculenta*, *Palmaria palmata*, *Laminaria hyperborea*, and *Ulva* spp. In particular, *Saccharina latissima* has also been farmed to investigate potential use of seaweed biomass as source of biofuel (biomethane) and chemicals (e.g. SeaGas, Macrofuel). In 2017, Queen's University harvested 20 tonnes of *S. latissima*, the UK's largest harvested seaweed batch as part of the SeaGas project. These encouraging results could help in opening up the supply chain for seaweed biomass and in development of the industry.

The current study focused on 4 seaweed species, which are most commonly farmed in the UK, and in some European countries; these are: *Saccharina latissima*, *Laminaria digitata*, *Alaria esculenta*, and *Palmaria palmata*.

1.1.2 Selection of the finfish aquaculture species for consideration

Selection of the finfish species to be considered in this study was made based on past aquaculture of finfish in the UK (see Figure 2) and future trends. In Europe, Atlantic salmon (*Salmo salar*) is, by mass, the major species farmed, comprising 48.3% of the total aquaculture output in 2014 (Clark and Bostock, 2017). This species is exploited heavily in Scotland and Norway (Marine Harvest, 2018) and demand for salmon remains high and is likely to increase.

Rainbow trout (*Oncorhynchus mykiss*) aquaculture represents 7% of the aquaculture sector of the UK (FAO, 2018b) although this is almost entirely freshwater culture. However, this is a well-established finfish species in the UK with potential in mariculture (Hambrey and Evans, 2016) and an important species to consider.

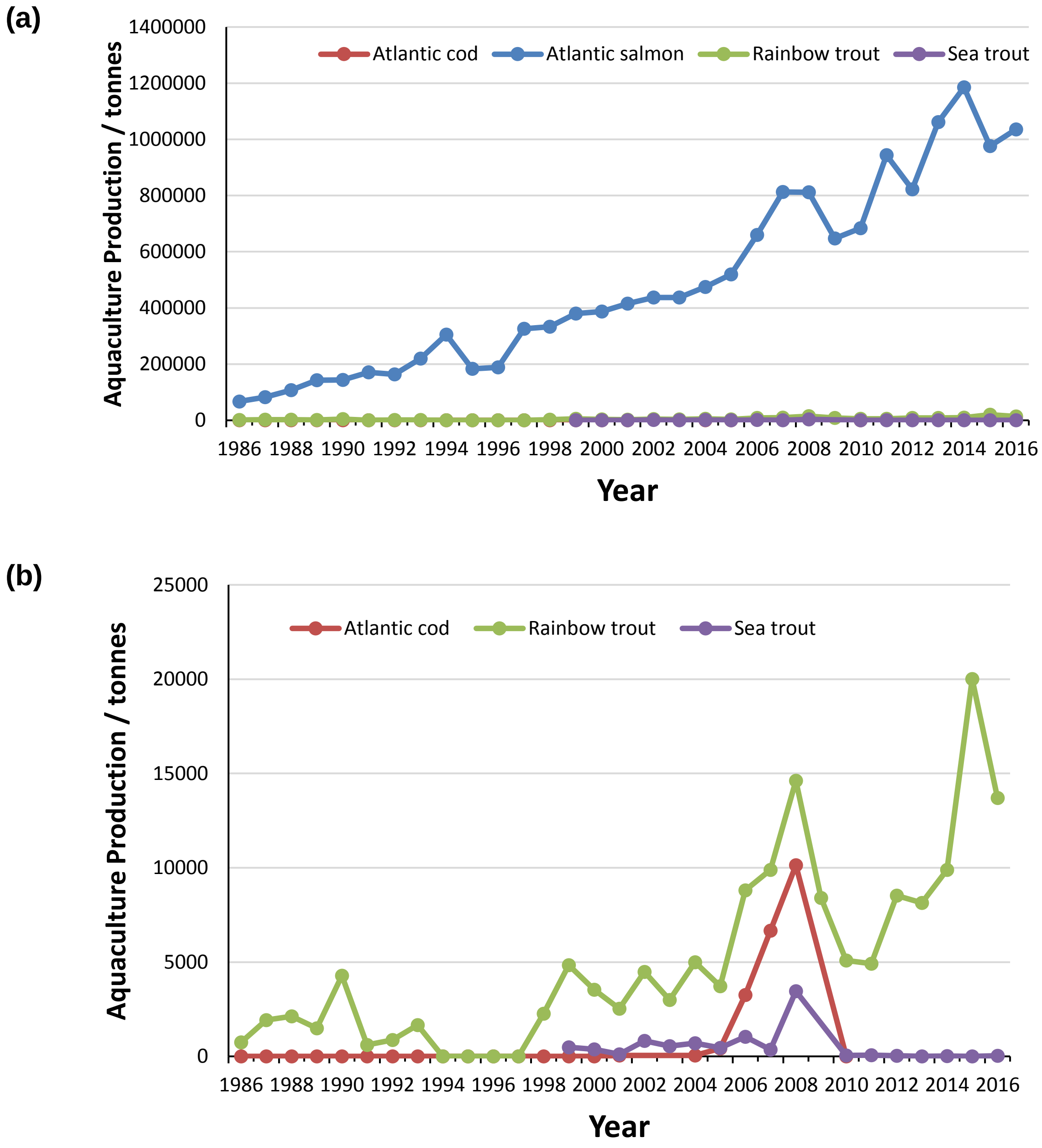
Brown (sea) trout (*Salmo trutta trutta*) is a close relative of rainbow trout and is present in coastal regions around the UK. There have been a few attempts at aquaculture of brown trout in sea cages and as a native species it has potential for future exploitation.

From 2001 to 2010 Atlantic cod (*Gadus morhua*) was cultured in the UK in response to collapsed stocks around the world (FAO, 2018c). As a native species that can be caught around the English coast this is another species that could potentially be exploited for aquaculture in English waters.

In summary the following finfish species are perceived to have the most economic viability and are therefore included in this study:

- Atlantic salmon (*Salmo salar*)
- Brown trout (*Salmo trutta trutta*)
- Rainbow trout (*Oncorhynchus mykiss*)
- Atlantic Cod (*Gadus morhua*)

Figure 2: Graph showing aquaculture production in the UK between 1986 and 2016. (a) all species; (b) data without Atlantic salmon. Production data downloaded from FAO using FishStatJ (FAO, 2018b).



1.1.3 Selection of the crustacean aquaculture species for consideration

The two most commercially important crustacean species in the UK are the Edible crab (*Cancer pagurus*) and the European lobster (*Homarus gammarus*). Landings of crab remain high and the amounts have been increasing since 2010 (Cefas Shellfish Team, 2017a). Furthermore, where available the data indicates that the numbers of edible crab caught remains below the maximum sustainable yield (Cefas Shellfish Team, 2017a). Therefore, in this study this species was not considered for aquaculture potential in the immediate future.

The latest review on the status of the wild stocks of European lobster around the UK shows that the overall landings of lobster has also increased since 2010 but that the areas from which animals are being caught is decreasing (Cefas Shellfish Team, 2017b). For those areas with sufficient data the status of the stock is low (Northumberland & Durham, South East South Coast), fairly low (Yorkshire) or moderate (South West) indicating possible future reduction in catch sizes.

As a result of overfishing in Scandinavia, lobster landings dropped by over 90% between 1930 to 1970 leading to the development of approaches to restock the wild populations (see Agnalt *et al.*, 2017 and references therein). Augmentation of wild lobster stocks by aquaculture methods such as the use of hatchery-reared stock has been attempted both in Europe and North America, but success has proven difficult to assess (Nicosia and Lavalli, 1999; Ellis *et al.*, 2015; Carere *et al.*, 2016). Recently, the UK has set up a "The National Lobster Hatchery" based in Cornwall (www.nationallobsterhatchery.co.uk). This centre of excellence has provided research and development into the production of juveniles for re-stocking, methods of culturing lobsters in sea-based containers and approaches to assess the success of re-stocking approaches (Ellis *et al.*, 2015; Bignell *et al.*, 2016; Halswell *et al.*, 2018).

The European lobster was considered a suitable species in this study for future aquaculture due to the pressures on the wild stocks in UK waters and the presence of a viable hatchery to supply juveniles for exploitation.

1.1.4 Selection of the bivalve mollusc aquaculture species for consideration

According to FAO figures, in the UK in 2016 the three major commercialised bivalve molluscs were blue mussel, Pacific oyster and native oyster (FAO, 2018b). Mussels accounted for 11% of the total (23,000 tonnes in 2016) aquaculture output, and therefore blue mussel (*Mytilus edulis*) was included in this study.

The Pacific oyster (*Crassostrea gigas*; 7983 tonnes production in 2016) and the native (flat) oyster (*Ostrea edulis*; 198 tonnes in 2016) were also included in this study as cultureed molluscs with the next greatest production. The Pacific oyster is a commercial aquaculture species that is cultivated around the world (see FAO, 2004). It is not native to the UK, unlike the native flat oyster, but was introduced into the UK for commercial exploitation from 1926 to 1978 (Utting and Spencer, 1992). The fast-growing and robust nature of Pacific oyster has resulted in an increase in its aquaculture and in 2012 it yielded 10 times the harvest weight of the native European oyster (Ellis *et al.*, 2015). Popularity of the native oyster has declined, driven largely by outbreaks of diseases such as *Bonamia oestrea* and *Martelisa refringnes* which has caused high levels of mortality in commercial oyster beds (see Laing and Spencer, 2006; OSPAR, 2009; Fariñas-Franco *et al.*, 2018).

There are two species of clam that have been commercially cultured in the UK, the Manila (Japanese carpet shell) clam (*Ruditapes philippinarum*) and the Northern Quahog (hard clam). Although the aquaculture of both has declined in recent years (Ellis *et al.*, 2015), commercial exploitation of the Manila clam remains high worldwide (FAO, 2018d) and the production tonnage in the UK is greater than that of the Northern Quahog (Ellis *et al.*, 2015). For these reasons only the Manila clam has been included in the study.

Similarly, there are 2 potential scallop species that have been cultured in the UK – the King Scallop (*Pecten maximus*) and the Queen Scallop (*Aequipecten opercularis*). In Scotland in 2012 production of the King Scallop was 7 tonnes versus just 0.4 tonnes of Queen scallop (T. Ellis *et al.*, 2015) and FAO statistics for 2016 (FAO, 2018b) indicate that production of the King scallop was 91 tonnes versus 24 tonnes for the Queen scallop. However, production of both species has varied between 1984 and 2016 with periods of higher yields from either species (FAO, 2018b). It is expected that environmental suitability will be similar for both species but based on recent production values only the King scallop will be considered in this study.

In summary, the bivalve mollusc species selected for this study were:

- *Crassostrea gigas* (Pacific oyster)
- *Ostrea edulis* (native (flat) oyster)
- *Mytilus edulis* (blue mussel)
- *Ruditapes philippinarum* (Manila clam)
- *Pecten maximus* (king scallop).

2 Methods

2.1 Approach

2.1.1 Overview

Spatial modelling and Geographical Information System (GIS)-based approaches are often used for site selection or suitability studies for aquaculture of fish and shellfish, and the literature provides multiple examples of these applications (for example Nath *et al.*, 2000; Longdill *et al.*, 2008; review by Kapetsky and Aguilar-Manjarrez, 2007). In contrast, there are limited studies where this analysis is applied to selection of sites for macroalgae farming (for example Radiarta *et al.*, 2011; Roesijadi, 2011).

GIS-based suitability modelling comprises the spatial overlay (intersection) of geo-data layers to find suitable sites for aquaculture, by identifying favourable environmental factors or constraints/limitations (Stelzenmüller *et al.*, 2017). In other words, a 'suitable' site could be defined as an area where the production of fish, shellfish or seaweeds is maximised and the conflicts (with other potential uses) are minimised (Kapetsky and Aguilar-Manjarrez, 2007; Roesijadi, 2011). Two sets of variables are usually needed for this type of analysis: selection factors (affecting productivity of the site; e.g. environmental variables), and selection constraints (e.g. competing uses for space; Roesijadi, 2011).

Selection factors, which have been used commonly for seaweed suitability modelling, include: current, bathymetry, wind (Kapetsky and Aguilar-Manjarrez, 2007); sea surface temperature, light climate, slope of the bottom (Radiarta *et al.*, 2011); chlorophyll concentration and salinity (Roesijadi, 2011).

The MMO carried out suitability modelling of seaweeds (project No. 1040; MMO, 2013), adopting four input layers (substrate type, seabed energy, depth and distance from shore), to investigate the suitability of the east and south coasts of England for seaweed farming (and other forms of aquaculture). Parameters such as turbidity (light climate), nutrient concentration, and sea surface temperature were not included in the analysis, due to limited data coverage in the study area. However, a follow-on report was produced by the MMO detailing the limitations; furthermore, the approach was also subsequently reviewed by Dr Sofia Franco[1] (Newcastle University).

The work described in this report is based on a GIS approach, developed in 2014 and shown in Figure 3, for investigating site suitability of seaweed farming off the East Anglian coast (Capuzzo *et al.*, 2014; commissioned by The Crown Estate). While the study in 2014 considered both selection factors and selection constraints, the study described in this report focuses only on the environmental selection factors. This is because the aim of this work is to produce maps of locations suitable for algal, finfish and shellfish growth and farming, which can then be used by the relevant authority (in combination with a selection of constraints) during spatial planning studies and coastal management. This work also aims to address some of

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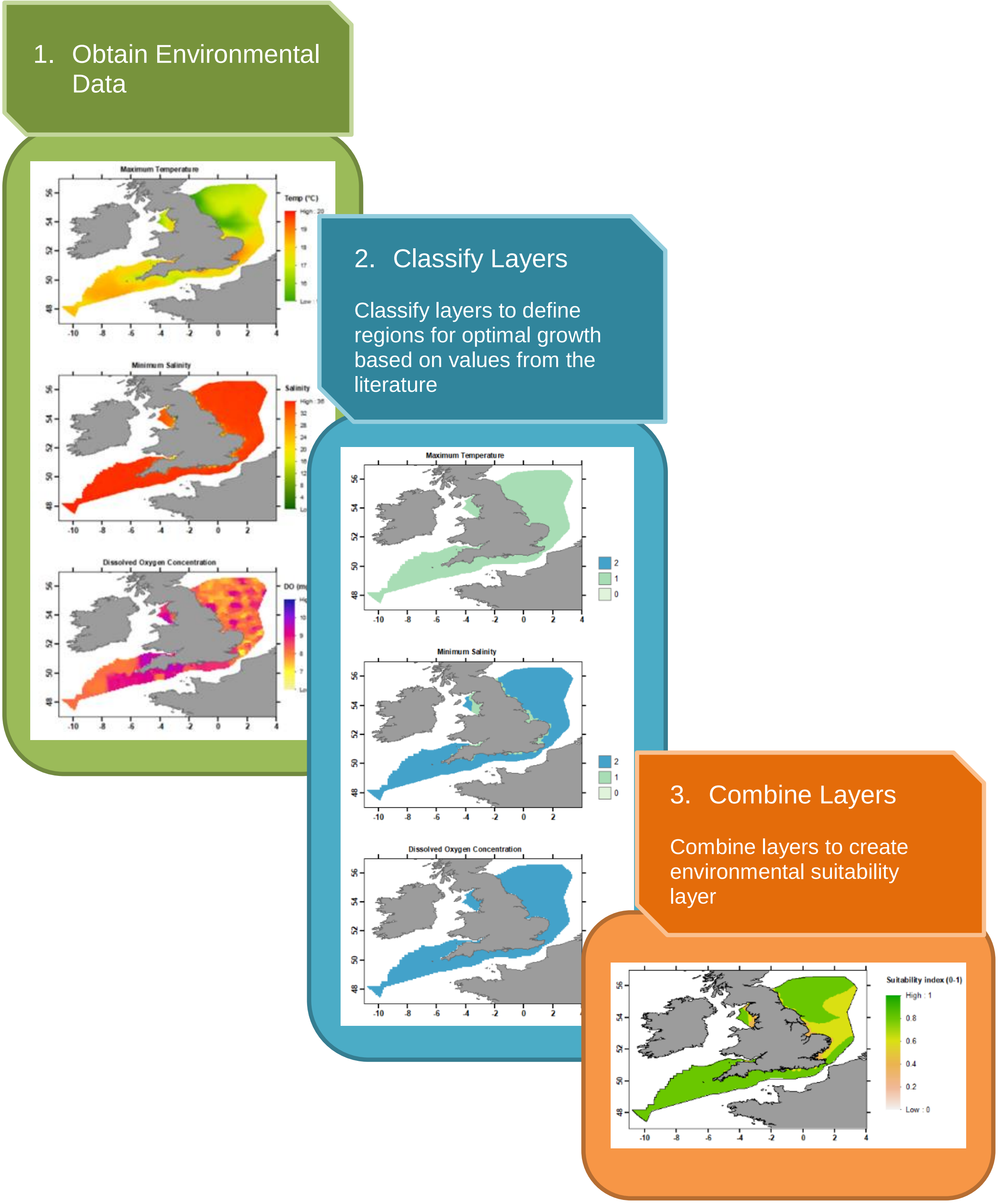
[1] http://www.seafish.org/media/1758345/acig_april2018_aquaassessment_marineplanning.pdf

the gaps identified in the MMO report (project No. 1040; MMO, 2013) by broadening the range of species and including environmental layers such as salinity, current and wave height, which were not considered in the previous work by the MMO.

Figure 3: Flow chart summarising the approach used for identifying areas suitable for aquaculture.



2.1.2 Data processing

Manipulation and display of raster and shapefile data was performed in ArcGIS version 10.5 using the toolboxes available under the Advanced licence. This included the Spatial Analyst Tools toolbox.

Generation of species-specific suitability raster data was performed in the software package R (version 3.5.1) using the IDE RStudio (version 1.1.383). The packages raster (Hijmans, R.J., 2019; version 2.8-19), rgdal (Bivand, R., Keitt, J. and Rowlingson, B., 2019; version 1.4-3) and rgeos (Bivand, R. and Rundel, C., 2019; version 0.4-3) were used to mask, reclassify and display the raster data.

2.2 Environmental variables investigated (biological selection factors)

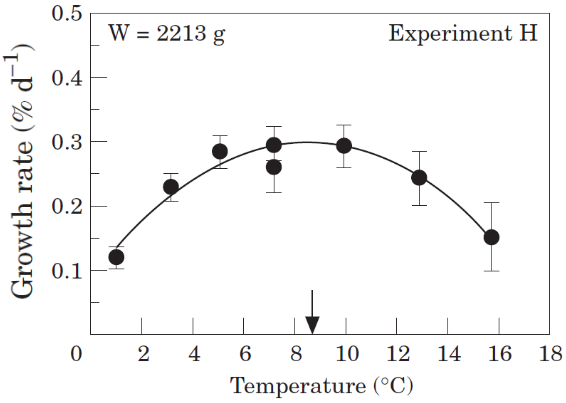
For the purposes of this study the environmental factors are considered separately and appropriately for each species. However, it should be noted that there is often a complex interplay between environmental factors. The environmental factors considered in this study are as follows:

2.2.1 Sea surface temperature

For all living organisms their ambient temperature plays an important role in their survival, growth and reproduction. Endothermic organisms maintain a constant body temperature above their surroundings, but this is an energy inefficient process and is often accompanied by slow growth and larger diets.

All the organisms considered in this report are ectotherms and their body temperatures are close to that of their surroundings. One major effect of this is on their metabolic rate which is much reduced at lower temperatures thereby affecting key processes such as digestion, assimilation (growth) and movement (Schulte, 2015). These effects can be simply described using thermal performance curves which tend to be unimodal and left skewed (Dell *et al.*, 2011). Generally, increasing the surrounding temperature, increases metabolism and therefore the growth rate of the organism increases also. This is especially true of finfish because the surrounding water is such a good conductor of heat and growth rates will rise to an optimal level, beyond which the rate decreases (Björnsson *et al.*, 2001; Elliott and Elliott, 2010). Above the optimum temperature heat loss to the environment exceeds gains from increased metabolism. The curvilinear growth profile for Atlantic cod is shown in Figure 4 and illustrates the presence of an optimal temperature for growth.

Figure 4: Example of the curvilinear effect of temperature on the growth rate of fish. Shown here is the effect on the growth rate in Atlantic cod (from Björnsson et al., 2001).



Temperatures above that which the organism normally experiences will cause high levels of mortality. This ‘critical temperature’ is specific to an organism and reflects their adaptations to minimising the effect of temperatures beyond the optimum. It is therefore important to consider the range over which the organism survives and grows, along with an optimal range when the growth rate is at its highest (Schulte, 2015).

2.2.2 Salinity of the water

Changes in salinity affect the osmotic regulatory capacity of organisms, and particularly the ability of living cells of taking up water through osmosis (Rivera-Ingraham, 2017). Organisms can respond to changes in salinity with osmotic acclimation; in general, it is possible to categorise species into euryhaline organisms (more tolerant to changes in salinity) and stenohaline organisms (less tolerant to changes in salinity). Fluctuations in salinity (e.g. in estuarine, intertidal or lagoon areas) can have severe effects on less tolerant organisms, potentially leading to mortality.

Adult finfish in seawater deal with an imbalance of a high level of salts in the external environment versus a comparatively lower level inside the cells of the organism. Dealing with this by osmoregulation is estimated to take 20 - 50% of the total energy output, although this may be an over-estimate (Bœuf and Payan, 2001). However, the effect of salinity on fish growth is multifactorial influencing the metabolic rate, intake of food, assimilation and hormonal action (Bœuf and Payan, 2001). Typically, highest growth rates are observed in intermediary salinity conditions (salinities of 8-20).

Marine shellfish (crustaceans and bivalve molluscs) living in coastal regions can experience large changes in the salinity of the surrounding water. Coastal salinity can fluctuate between near freshwater (near 0 salinity) to hypersaline seawater in supratidal pools (>150 salinity) (Rivera-Ingraham and Lignot, 2017). To acclimatise to changes in salinity the marine shellfish must make cellular adjustments to prevent loss of water and turgor pressure (hypertonic challenge) or uptake of water or cell lysis (hypotonic challenge). This is achieved through a combination of changes to membrane permeability, osmotic effectors in the cytosol, active transport processes and the production of ammonia (Rivera-Ingraham and Lignot, 2017). These processes require an increase in energy expenditure and therefore specific species balance their energy budgets according to potential niches that can be occupied (Rivera-Ingraham and Lignot, 2017). Most bivalves and crustaceans are osmoconformers and they keep their internal conditions isosmotic to their environment (Rivera-Ingraham and Lignot, 2017).

The salinity of water changes in response to varying water temperature. However, the wide fluctuations in salinity are observed in transitional and coastal waters, subjected to river runoff. Estuarine areas can have large fluctuations in salinity due to freshwater input from rivers which can vary seasonally. In some coastal lagoons the water movement is restricted, and salinity increases as water evaporates. This can also occur in the intertidal zone and in particular in coastal rock pools.

As the unit of salinity is dimensionless no unit for salinity will be used in this report. For ease of reference the reader should consider values as practical salinity units (psu).

2.2.3 Light availability

Without light (specifically PAR, photosynthetically available radiation), seaweeds (as well as any other plant) would not be able to carry out photosynthesis and therefore survive. However, too much light has also detrimental effects as it can lead to cellular damage and death (termed photoinhibition; see review by Hanelt and Figueroa, 2012).

2.2.4 Phytoplankton (chlorophyll) levels

For filter feeder organisms, such as mollusc bivalves, the availability of phytoplankton biomass is important, as microalgae can represent the major food source for these organisms. Studies (e.g. Laing and Spencer, 2006; Strand *et al.*, 2016) have shown that up to 85% of growth performance differences between sites culturing bivalves is due to the combined effects of water temperature and primary productivity (i.e. phytoplankton concentration).

Phytoplankton concentrations show seasonal fluctuations in relation to changes in the environmental conditions (i.e. nutrient and light availability and temperature) and bivalves cope by supplementation of their diet with particulate organic matter. Furthermore, phytoplankton are difficult to characterise to species level and the relative nutritional value is not known for many species.

Phytoplankton are autotrophic, using photosynthesis to fix carbon and generate organic biomass. This process requires chlorophyll pigments and the concentration of these pigments in the sea water can be used to assess the phytoplankton levels. This is useful as it allows remote sensing by satellite over large areas (see Synder *et al.*, 2017 for application of this process to aquaculture site selection along the Maine coast). However, using this as a proxy for the phytoplankton levels has been questioned (Bourlès *et al.*, 2009) with studies showing a disparity between chlorophyll levels and phytoplankton abundance and/or biomass. It is suggested that where environmental conditions are relatively stable chlorophyll levels are a good indicator of phytoplankton (Ren and Schiel, 2008) but this association is less strong in more varied ecosystems. In general, the ratio between carbon and chlorophyll in phytoplankton cells is not fixed but changes during the year and with location (e.g. (Jakobsen and Markager, 2016; Lyngsgaard *et al.*, 2017).

2.2.5 Nutrient concentration

Seaweed require nutrients (e.g. nitrogen and phosphorus) for growth and metabolic processes. The uptake rate of the dissolved nutrients from the surrounding water is affected by factors such as light availability, temperature, desiccation, water movement, and the chemical form of nutrients (Harrison and Hurd, 2001). The rate is not constant with time but may vary depending on the level of nutrients in the nutrient-pools in the plant tissue (i.e. whether the plant is in a nutrient-limited stage or not; (Harrison and Hurd, 2001)). In this study we focused on availability of total oxidised nitrogen (TOxN), nitrate and nitrite concentrations.

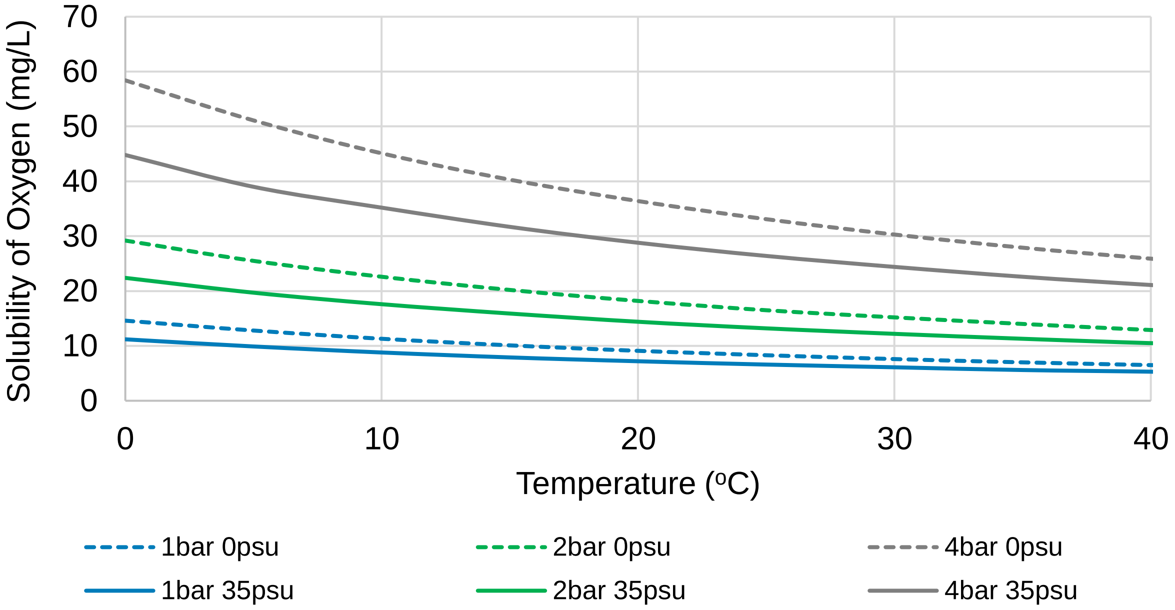
2.2.6 Dissolved oxygen concentration

The concentration of dissolved oxygen (DO) in water is influenced by many factors including water temperature, salinity, atmospheric pressure, water depth and biological activity (i.e. photosynthesis and respiration). There is an inverse relationship between the temperature of water and the concentration of oxygen dissolved in it (Benson and Krause, 1984; Garcia and Gordon, 1992). The DO concentration of seawater is typically around 8-11mg/L.

Most marine organisms are poikilotherms and thus have a metabolic rate that is predominantly controlled by the surrounding water temperature. Any increase in temperature results in an increase in metabolic rate with a subsequent increase in oxygen uptake and growth. However, at increased temperatures oxygen availability decreases as the amount of oxygen dissolved in the seawater reduces (see Figure 5). For example, at 1 atmosphere pressure seawater at 5°C has 9.9mg/L DO compared to 7.2mg/L for water at 20°C (Benson and Krause, 1984; Garcia and Gordon, 1992). Furthermore, a decrease in salinity results in an increase in DO. In freshwater, at 1 atmosphere pressure the DO is 12.8mg/L at 5°C and 9.1mg/L at 20°C (Benson and Krause, 1984; Garcia and Gordon, 1992).

Factors which can affect the level of oxygen dissolved in the water include movement of the water, mixing of the water with air and the presence of marine organisms. In particular, biofouling of aquaculture apparatus can lead to an increase in microorganism growth (decomposers) which increase the Biological Oxygen Demand producing localised reductions in DO levels (Fitridge *et al.*, 2012).

Figure 5: The effect of temperature and pressure on the concentration of dissolved oxygen. Taken from Engineering ToolBox, (2005). Oxygen-Solubility in Fresh Water (0psu) and Sea Water (35psu). Data available online at: www.engineeringtoolbox.com/oxygen-solubility-water-d_841.html, accessed 10/06/2019.



2.3 Environmental factor spatial layers

In order to determine the suitability of aquaculture in UK waters, data for the applicable environmental factors needed to be sourced and adapted to a suitable format for the project. This section details the methods used in each case.

The environmental layers used were:

1. Sea Surface Temperature (Lowest 2.5% quantile recorded)
2. Sea Surface Temperature (Highest 97.5% quantile recorded)
3. Sea Water Salinity (Lowest 2.5% quantile recorded)
4. Sea Water Salinity (Highest 97.5% quantile recorded)
5. Dissolved Oxygen Concentration
6. Light Penetration
7. Total Oxidised Nitrogen Concentration (Nutrient layer)
8. Chlorophyll Concentration (Phytoplankton layer).

In most aquaculture methods, the organisms are cultivated close to the sea surface (see Section 5). For example, seaweed cultivation occurs in the upper part of the water column (between 1 and 4m depth); finfish cages are typically 15-20m deep and bivalve bottom culture is at depths no greater than 40m. Therefore, the environmental variables for this study were identified for depths down to 25m in the water column.

2.3.1 Sea surface temperature

Daily sea surface temperature data for a 9-year period (2006-2014) was obtained from the Ocean Sea Temperature and Ice Analysis Product (OSTIA; see description in Donlon *et al.*, 2012) of the UK Met Office with delivery via the Copernicus Marine data portal (http://marine.copernicus.eu/). Particularly, the following products were used:

- SST_GLO_SST_L4_REP_OBSERVATIONS_010_011
- SST_GLO_SST_L4_NRT_OBSERVATIONS_010_001).

The minimum and maximum temperature values (calculated as the 2.5th and 97.5th percentile, respectively) were derived on an annual basis and used to set a temperature range. In this way it can be expected that at least 95% of daily temperature values fell within this range. Gaps in the data layers were filled in using an Inverse Distance Weighted (IDW) algorithm using a search radius of 12 points in ArcGIS 10.5. The final raster layer had a cell size of 0.029982004 degrees (GCS_WGS_1984) which approximates to 3.3km^2. The raster layers are presented in Figure 11 and data sources in Annex A1.

2.3.2 Water salinity

A dataset of all available measurements of salinity for the upper 25 m of the water column was prepared, using data compiled for the UK Eutrophication Comprehensive Assessment (from 1990-2014; https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017/), with additional data from the UK Environment Agency (2007-2012; http://data.cefas.co.uk/#/View/19600).

As with temperature, the extreme values of the 95% data interval (2.5th and 97.5th, percentile values), minimum and maximum salinity, were calculated on an annual basis and used to set a salinity range, using a 1/12th degree grid. The dataset was cropped to include only stations within the English Economic Exclusion Zone. Sampling stations were not equally distributed across the study area, therefore inverse distance weighted interpolation was used to interpolate onto a 1/12th degree grid, using at least 3 data points and a search radius of 1/3rd degree to produce a suitable layer of salinity. The final raster layer had a cell size of 0.0833333 degrees (GCS_WGS_1984) which approximates to 9.3km^2. The raster layers are presented in Figure 12 and data sources in Annex A1.

2.3.3 Dissolved oxygen

All available measurements of water column dissolved oxygen concentration during the annual period of March to October were prepared, using data compiled for the UK Eutrophication Comprehensive Assessment (1990-2014; https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017/), with additional data from the UK Environment Agency (2007-2012; http://data.cefas.co.uk/#/View/19600). As for salinity, the dataset was cropped to include only stations within the English Economic Exclusion Zone. Sampling stations were not equally distributed across the study area, therefore inverse distance weighted interpolation was used to interpolate onto a 1/12th degree grid, using at least 3 data points and a search radius of 1/3rd degree to produce a suitable layer of dissolved oxygen concentration.

Due to limited data availability, there were some small gaps in coverage of the English coast of this layer, notably in Lyme Bay. Data from ERSEM, Plymouth Marine Laboratory (Lessin *et al.*, 2018) was used to fill these data gaps. The model provides monthly estimates of various marine parameters and the data made available under the Creative Commons Attribution 4.0 International Licence (http://creativecommons.org/licenses/by/4.0/legalcode). The dissolved oxygen concentration output from the model was extracted between 1st Jan 1990 and 31st December 2018 for the depths of 25m or above and a mean value was taken. Using ArcGIS 10.5 this data was used to fill data gaps in the south-west extent of the dissolved oxygen layer. Any remaining gaps were filled by using an Inverse Distance Weighted algorithm in ArcGIS 10.5 with a 12 point search radius to produce the completed dissolved oxygen layer with a cell size of 1/12 degrees. The raster layer is presented in Figure 13a and data sources in Annex A1.

2.3.4 Light penetration

Daily maps of the light attenuation coefficient from MODIS (K_d(PAR); Gohin *et al.*, 2002), generated by Ifremer (Brest, France; http://www.ifremer.fr/nausicaa/marcoast/index.htm), were averaged by month across 10 years (from 2002 to 2012). The estimated K_d(PAR) for spring (March/April/May) was used to calculate the depth at which the available light is equivalent to 10% of surface light, using Equation 1.

$$E_{Z10\%} = 0.1 \times E_0 = \ E_0 \times e^{-K_d(PAR) \times Z10\%} \qquad (1)$$

Where $E_{z10\%}$ is the irradiance (Photosynthetic Available Radiation, PAR) at depth $z_{10\%}$; E_0 is the irradiance (PAR) just below the surface; and $z_{10\%}$ is the depth at which the irradiance is 10% of the surface irradiance.

The 10% surface light depth was chosen as descriptor of the light climate to ensure that a portion of the water column fell in an optimal range of irradiance for photosynthetic activity (i.e. not light limited). The final raster layer had a cell size of 0.029982004 degrees (GCS_WGS_1984) which approximates to 3.3km^2. The raster layer is presented in Figure 13b and data sources in Annex A1.

2.3.5 Total oxidised nitrogen

All available measurements of water column TOxN for the upper 25m of the water column during the winter months (November to February) were prepared, using data compiled for the UK Eutrophication Comprehensive Assessment (1990-2014; https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017/), with additional data from the UK Environment Agency (2007-2012; http://data.cefas.co.uk/#/View/19600). As for salinity, the dataset was cropped to include only stations within the English Economic Exclusion Zone. Sampling stations were not equally distributed across the study area, therefore inverse distance weighted interpolation was used to interpolate onto a 1/12th degree grid, using at least 3 data points and a search radius of 1/3rd degree to produce a suitable layer of nutrient concentration.

TOxN concentration was estimated from measurements in the upper 25m of the water column, therefore it was assumed that TOxN concentration was uniform throughout this part of the water column.

Due to limited data availability, there were some small gaps in coverage of the English coast of this layer, notably in Lyme Bay. Data from ERSEM, Plymouth Marine Laboratory (Lessin *et al.*, 2018) was used to fill these data gaps. The model provides monthly estimates of various marine parameters and the data made available under the Creative Commons Attribution 4.0 International Licence (http://creativecommons.org/licenses/by/4.0/legalcode). The total nitrate concentration output from the model was extracted between 1st Jan 1990 and 31st December 2018 for the depths of 25m or above and a mean value was taken. Using ArcGIS 10.5 this data was used to fill data gaps in the south west extent of the total oxidised nitrogen layer.

The final TOxN layer was completed using ArcGIS 10.5 by using an Inverse Distance Weighted algorithm with a 12-point search radius to fill in data gaps using interpolation. The raster layer is presented in Figure 14a and data sources in Annex A1

2.3.6 Chlorophyll (phytoplankton)

In situ measurements of chlorophyll were preferred over remotely acquired satellite data because they are inherently more reliable in complex coastal waters. Estimates of chlorophyll from satellite data can be influenced by variable levels of Suspended Particulate Matter (SPM) and Coloured Dissolved Organic Materials often experienced in case-2 waters (coastal waters).

All available measurements of water column chlorophyll for the upper 25m of the water column during the months March to October inclusive (coincident with the phytoplankton growing season) were prepared, using data compiled for the UK Eutrophication Comprehensive Assessment (2000-2014; https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017/), with additional data from the UK Environment Agency (2007-2012; http://data.cefas.co.uk/#/View/19600). Chlorophyll samples were analysed by different techniques such as fluorescence, spectrophotometry and HPLC; only HPLC provides a measurement of chlorophyll-a, while fluorescence, for example, cannot distinguish between chlorophyll-a and chlorophyllide. Therefore, for this study we simply refer to chlorophyll.

As for salinity, the dataset was cropped to include only stations within the English Economic Exclusion Zone. Sampling stations were not equally distributed across the study area, therefore inverse distance weighted interpolation was used to interpolate onto a 1/12th degree grid, using at least 3 data points and a search radius of 1/3rd degree to produce a suitable layer of nutrient concentration.

To fill in any gaps in the data layer, satellite data from the Ocean Colour Climate Change Initiative dataset was used (downloaded from http://www.esa-oceancolour-cci-org on 28/02/2019). Data from 2000 to 2018 was extracted for the months March to October inclusive and a spatial mean was generated in R using the Raster package. Using ArcGIS 10.5 this data layer was used to fill in gaps from the *in situ* layer and resulted in a raster layer with a resolution of 1/12 degree. The raster layer is presented in Figure 14b and data sources in Annex A1.

2.4 Technical constraints

Environmental variables which are more likely to affect (and pose a limit to) the infrastructure of the farm (e.g. type of anchoring system), were considered under as technical constraint level and not included in the suitability layer. The technical constraint layers used were:

1. average water current
2. average peak wave height
3. bathymetry
4. seabed substrate

Installations at sea need to withstand a high-energy environment (wave, tide, storm, wind), causing challenges related to the aquaculture infrastructures, operation and maintenance (Buck and Grote, 2018). However, there is limited data available in literature on the maximum value of wave height and/or current which can be withstood by farms.

Information on seabed substrate are relevant when considering the type of anchoring required for the farm; while bathymetry can affect the type and cost of engineering infrastructure.

These technical constraints are also environmental factors that influence growth of the organisms. For example, seaweeds require water movement to allow for nutrient replenishment in the boundary layer around the blade. Water movement is also important for guaranteeing good oxygen levels in finfish farms or for providing food for filter feeder organisms. However, the effects of technical constraints with environmental origins on species growth is minor compared with the effects of the environmental/biological layers, listed in Section 2.3. Further, such factors can be artificially manipulated by the culturing technique. For example, unfavourable seabed substrate can be addressed by using rope culture (such as with mussels or seaweed) and finfish sea cages are used to restrict access to the full bathymetric range.

2.5 Data provenance

In the generation of some of the layers used in this report some of the layers are built from several different sources. These sources are:

- *in situ* measurements
- satellite data
- parameter data obtained from models
- values obtained by interpolation

To allow assessment of the spatial provenance of the data used to generate the suitability layers, each layer has an accompanying data provenance layer. This contains an indicator of the provenance for each grid within the raster plot. These raster layers are shown in Annex 1 and the percentage for each data type is shown in Table 1 below.

While salinity data was obtained mainly from *in situ* measurements, sea surface temperature and light penetration were estimated from satellite measurements, with limited interpolation. Chlorophyll concentration measurements were mainly from *in situ* observations although satellite data was necessary to cover areas with reduced *in situ* data. DO and TOxN required a combination of *in situ*, modelled data and interpolation; this was due to limited observations (particularly offshore; Table 1).

Table 1: Provenance of the data used to generate the environmental and technical constraint layers in the study. *In situ* data refers to the point data source plus the inverse distance weighted interpolation around this point.

Data Layer	Percentage of Data of each type in the Layer			
	In situ	Satellite	Model	Interpolated
Sea Surface Temperature	0	97.6	0	2.4
Salinity	94.8	0	0	5.2
Dissolved Oxygen	46.5	0	25.7	27.8
Light Penetration	0	97.6	0	2.4
Total Oxidixed Nitrogen	67.7	0	14.6	17.8
Chlorophyll	76.6	23.4	0	0
Wave Height	0	0	98.1	1.9
Current Speed	0	0	94.3	5.7
Bathymetry	99.2	0	0	0.8
Substrate	99.3	0	0	0.7

3 Identification of species-specific environmental thresholds

3.1 Overview of optimal physiological conditions

A literature review was performed to identify the optimal physiological conditions for the growth of selected possible aquaculture species. These represent the ideal conditions that would maximise growth of an individual of that species in the natural environment.

3.2 Seaweed species

For the seaweed species the following environmental variables were considered:

a) **Sea surface temperature.** The ambient temperature of the seaweed affects the growth rate as it influences the rate of metabolic processes
b) **Salinity.** The surrounding water salinity affects osmotic processes in the cell thereby influencing the growth rate
c) **Light depth.** Light intensity affects the rate of photosynthesis in the seaweed and therefore affects the growth rate.
d) **Nutrient level.** Nutrients (nitrates and nitrites; TOxN) are required to produce of new molecules in the seaweed and therefore their limitation prevents growth.

The results of a survey of the literature on cultivation of seaweed and the influence of these factors is described in this section.

3.2.1 *Saccharina latissima*

Saccharina latissima, or sugar kelp, can grow to 1.5 m in length; it is characterized by a crinkly, dimpled, ruffled appearance and has a light to dark brown colour (Figure 6; (Bunker *et al.*, 2017). The frond is undivided, without a midrib, and it has a short stipe; it grows quickly from late winter to spring (White and Marshall, 2007).

Figure 6: *Saccharina latissima* exposed at low tide (photo and copyright Dr Keith Hiscock, http://www.marlin.ac.uk/species/detail/1375).

It is present on rocky substrata in disturbed habitats (e.g. sand scoured) as well as in sheltered sea lochs (Bunker *et al.*, 2017). It is often found on unstable rocks and boulders, with adaptations like its flexible stipe reducing leverage and thus movement on the boulder (White and Marshall, 2007). Sugar kelp prefer low to moderate water movements (between 0.1m/s to 1m/s) but can grow well also in strong currents up to 1.5m/s (Kerrison *et al.*, 2015).

Thresholds for environmental variables for *S. latissima* are given in Table 2.

Table 2: Details of the thresholds chosen for *Saccharina latissima* for each environmental variable

Environmental Factor	Optimal	Sub-optimal	Not suitable	Reference
Minimum SST (°C)	>5	2-5	<2	Bolton and Lüning, 1982; Kerrison *et al.*, 2015
Maximum SST (°C)	<16	16-18	>18	Bolton and Lüning, 1982; Kerrison *et al.*, 2015
Minimum Salinity	>24	15-24	<15	Kerrison *et al.*, 2015
K_d(PAR) 10% light depth (m)	>2	1-2	<1	van der Molen *et al.*, 2018
Winter TOxN (mmol/m^3)	>10	4-10	<4	Broch and Slagstad, 2012; Kerrison *et al.*, 2015

3.2.2 *Laminaria digitata*

Laminaria digitata is a kelp usually less than 1.5m long, with a leathery sheet-like blade, oval in shape and divided in linear segments, digitate (Bunker *et al.*, 2017; Figure 7). It has a shiny-brown colour, and it is perennial (living up to 10 years; Bunker *et al.*, 2017), growing rapidly from February to July (Hill, 2008). It can be found on rocky substrata, from very exposed to very sheltered conditions (Bunker *et al.*, 2017); it flourishes in moderately exposed areas or in sites with strong current (Hill, 2008).

Figure 7: *Laminaria digitata* individual exposed at low tide (photo and copyright Judith Oakley; https://www.marlin.ac.uk/species/detail/1386).

Thresholds for environmental variables for *L. digitata* are given in Table 3.

Table 3: Details of the thresholds chosen for *Laminaria digitata* for each environmental variable and reference.

Environmental Factor	Optimal	Sub-optimal	Not suitable	Reference
Minimum SST (°C)	> 5	2-5	<2	Kerrison *et al.*, 2015
Maximum SST (°C)	<16	16-18	>18	Kerrison *et al.*, 2015
Minimum Salinity	>20	15-20	<15	Kerrison *et al.*, 2015
K_d(PAR) 10% light depth (m)	>2	1-2	<1	Same as *S. latissima*
Winter TOxN (mmol/m^3)	>10	4-10	<4	Broch and Slagstad, 2012; Kerrison *et al.*, 2015

3.2.3 *Alaria esculenta*

Alaria esculenta, or winged kelp, has a spear-shaped frond with a distinct midrib throughout the length of the blade, and can grow up to 1.5 m (Bunker *et al.*, 2017; Figure 8). The colour can be yellowish, olive-green or rich brown (Tyler-Walters, 2008). It is typically found in exposed and very exposed rocky shores (Bunker *et al.*, 2017).

Figure 8: *Alaria esculenta* at the water's edge (photo and copyright Judith Oakley; https://www.marlin.ac.uk/species/detail/1291).

Thresholds for environmental variables for *A. esculenta* are given in Table 4

Table 4: Details of the thresholds chosen for *Alaria esculenta* for each environmental variable

Environmental Factor	Optimal	Sub-optimal	Not suitable	Reference
Minimum SST (°C)	>4	2-4	<2*	Tyler-Walters, 2008; Fredersdorf *et al.*, 2009
Maximum SST (°C)	<16	16-17	>17*	Sundene, 1962; Lüning, 1984
Minimum Salinity	>20	15*-20	<15*	Karsten *et al.*, 2003; Fredersdorf *et al.*, 2009
K_d(PAR) 10% light depth (m)	>2	1-2	<1	Same as *S. latissima*
Winter TOxN (mmol/m^3)	>10*	4*-10*	<4*	Not known, same as *S. latissima, L. digitata*

* - Values estimated from other studies.

There is limited information regarding optimal ranges of environmental variables for growth of *A. esculenta*, therefore some assumptions were made. Particularly:

- Minimum temperature: Fredersdorf *et al.* (2009) reported that *A. esculenta* can tolerate temperatures of 4°C. As this is broadly similar to the lowest optimal temperature for *S. latissima* and *L. digitata*, the same threshold as these two kelps of 2°C for unsuitable minimum temperature was used for *Alaria*
- Maximum temperature: this species optimal temperature is <16°C (Lüning, 1984); however, there is very limited information of tolerance and growth rate of this species above this temperature. The limit of 17°C was estimated according to Birkett *et al.*, (1998), that suggested to calculate lethal limit as 1-2°C above growth limit
- Minimum salinity: Fredersdorf *et al.* (2009) showed that *Alaria* tolerates salinity between 20 and 34. Karsten *et al.* (2003) observed limited changes to the photosynthetic capacity of Arctic *Alaria* (quantum yield) between salinity 10 and 50. The threshold of 15 was chosen as an average value between the lowest salinities of these two studies
- TOxN: the literature search did not provide relevant reference on optimal nutrient ranges for *Alaria*, hence the same ranges as *S. latissima* and *L. digitata* were used.

3.2.4 *Palmaria palmata*

Palmaria palmata, or dulse, is a flat red seaweed, which can have either a simple blade (with/without marginal proliferations) or with branches, and can have a leathery texture (Bunker *et al.*, 2017; Figure 9). Dulse has a purplish or brownish-red colour and grows on rocks or as epiphyte on stipes of other plants (e.g. Forest Kelp, *L. hyperborean*, and *L. digitata*), in sheltered or moderately exposed areas (Werner and Dring, 2011; Bunker *et al.*, 2017).

Figure 9: *Palmaria palmata* fronds (photo and copyright Dr Keith Hiscock, https://www.marlin.ac.uk/species/detail/1405)

Thresholds for environmental variables for *P. palmata* are given in Table 5.

Table 5: Details of the thresholds chosen for *Palmaria palmata* for each environmental variable

Environmental Factor	Optimal	Sub-optimal	Not suitable	Reference
Minimum SST (°C)	>6	2-6	<2	Morgan and Simpson, 1981; Werner and Dring, 2011
Maximum SST (°C)	<15	15-18	>18	Morgan and Simpson, 1981; Werner and Dring, 2011
Minimum Salinity	>32	30-32	<30	Morgan and Simpson, 1981; Hill, 2008
K_d(PAR) 10% light depth (m)	>1*	0.5*-1*	<0.5*	Not known
Winter TOxN (mmol/m^3)	>10*	4*-10*	<4*	Not known

* - Values estimated from other studies.

As for *Alaria esculenta*, limited information was available in literature on optimal environmental ranges for growth of *Palmaria palmata*. Some of the thresholds were selected based on the following considerations:

- Minimum and maximum temperatures: Morgan and Simpson, (1981) tested that *P. palmata* grows well between 6°C and 14°C but poorly at 18°C, while Werner and Dring (2011) identifying the optimal temperature range between 8°C and 12°C, with limited growth above 15°C. At the same time the latter authors indicated that winter temperature (above ice-formation) is not considered damaging. So, the limit of 2°C was chosen in consistency with *L. digitata* (as *Palmaria* can be an epiphyte of this kelp)

- Minimum salinity: *P. palmata* presents stenohaline features, as it is a typical sublittoral red algae, adapted to full, stable salinity. Werner and Dring (2011) recommend avoiding cultivation in brackish water and estuaries; in fact this species presented high mortality at a salinity of 15 (Karsten *et al.*, 2003). Morgan *et al.*, (1980) reported that 32 is the optimal salinity for *P. palmata*. Based on this information an unsuitable level of 30 was assumed allowing 2 points of salinity tolerance between an unsuitable level and the optimal value of 32
- Light climate: this species lives in natural shaded canopy of kelp blades, so high light intensity in summer can cause bleaching; when farmed, it may be necessary to lower the algae deeper in the water column (Werner and Dring, 2011). Based on this consideration, it was assumed that species can live in more turbid waters than the other seaweed species considered in this study and therefore the threshold levels are lower than those for the other seaweed species.

3.3 Finfish species

For all finfish species there is good agreement that the three main environmental drivers for growth and are therefore considered here are:

- Sea surface temperature
- Salinity
- Dissolved oxygen concentration

Fish are ectothermic and are therefore profoundly influenced by the temperature of the water surrounding them. Different species are adapted for survival in different ranges of temperatures and therefore have preferred ranges both for survival and reproduction. At a broad level a fish species can be considered to be coldwater (upper lethal limit of about 25°C and optimum range of 5-20°C), warmwater (upper lethal limit of 36°C and optimum range of 20-32°C) or coolwater (upper lethal limit of around 30°C and optimum range of 20-28°C) (McCullough, 2001). The finfish species in this report are all coldwater fish species.

In salmonids (Atlantic salmon, brown trout and rainbow trout) an important factor in the effect of temperature change on metabolism is acclimatisation. Any effect on the physiology and behaviour of the fish is affected by its recent thermal experience. Any extreme temperatures are likely to be reached gradually in nature and therefore studies are selected that have a relatively long acclimatisation period (at least two weeks) before lethal temperatures are investigated. Using these approaches there are two different temperature extremes that can be recorded; the Incipient Lethal Temperature at which 50% survival can occur over a period of 7 days and the Ultimate or Critical Lethal Temperature at which the fish cannot survive even for short periods of time (Elliott and Elliott, 2010). For this study the unsuitable region is defined using the Incipient Lethal Temperature. This ensures that the species can survive a 7-day exposure to the maximum temperature identified.

An increase in ambient temperature of the fish will increase the metabolic rate of the fish as enzymatic pathways function faster (Elliott and Elliott, 2010). To compensate, the fish must deliver more oxygen and glucose to muscles and other body organs and so the heart and ventilation rate will increase (Elliott and Elliott, 2010). At first, such increases are within physiological constraints and therefore growth rate is increased. However, any increase in temperature results in a larger thermal gradient and therefore an increase in total heat loss to the environment, more energy expenditure on body processes and changes to behaviours such as feeding (Elliott and Elliott, 2010). As a consequence, at a certain temperature the increase in growth rate stops and begins to fall with increased temperature. This optimal temperature is different between juveniles (fingerlings and fry) and adults and is dependent on the surface area to volume ratio of the fish (Elliott and Elliott, 2010; Handeland *et al.*, 2008; Oppedal *et al.*, 2011).

In adult fish the salinity of the surround environment is a key factor in controlling growth. The interaction of salinity on growth is complex and can affect metabolic rate and digestion in the organism (Bœuf and Payan, 2001). Usually the best growth rate is observed in intermediary salinity conditions typified by brackish water (Bœuf and Payan, 2001). At higher salinities an increased metabolic rate is needed to perform osmoregulation, and this impacts the available energy budget for growth (reviewed in Bœuf and Payan, 2001). However, caution must be taken when considering this parameter for mariculture of finfish. In culture the fish can be fed to satiation and therefore this constraint becomes an economic rather than a biological consideration (Björnsson and Steinarsson, 2002; Oppedal *et al.*, 2011).

There is evidence that increased swimming speed in fish under aquaculture conditions can improve growth rates and meat quality (Jobling *et al.*, 1993; Castro *et al.*, 2011; Tudorache *et al.*, 2013). Best growth rates have been characterised by a swimming speed of 1 body length per second. An increase in the swimming speed of fish can be produced by siting culture pens in strongly tidal regions or in exposed areas with high wave velocity. Fish swimming performance can be categorised into three groups (Plaut, 2001):

- Sustained – speeds that can be maintained for over 200 minutes using aerobic respiration
- Prolonged – speeds that can be maintained for 20s to 200 minutes aerobically and results in fatigue in the fish
- Burst – this is the highest speed the fish can attain but only over a short period of time.

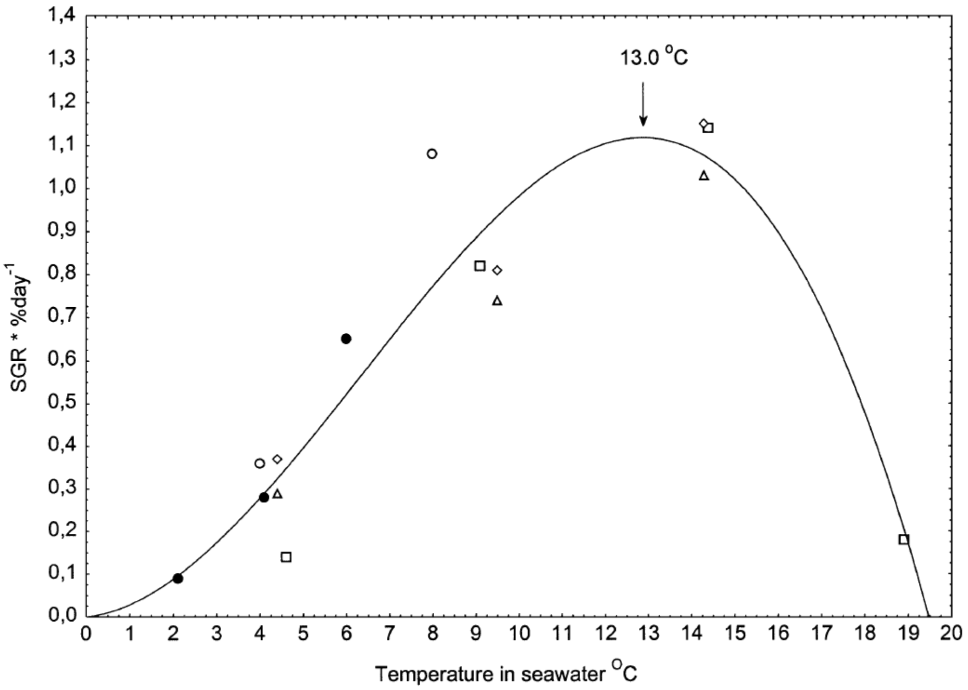
In this study the current speed is not considered as an environmental constraint. However, the prolonged speed that the four species of finfish can withstand will be considered when setting threshold levels.

3.3.1 Atlantic salmon (*Salmo salar*)

Production of Atlantic salmon in open sea cages involves growing on of juvenile smolts to adult fish for harvest. Temperature is a key factor affecting growth of salmon smolts and adults. In the literature there are a number of experiments that document the temperature to achieve optimal growth in Atlantic salmon. These include experiments performed in regulated tanks (Jonsson *et al.*, 2001; Larsson and Berglund, 2006; Handeland *et al.*, 2008; Elliott and Elliott, 2010) and more recent work looking at temperature profiles in “at-sea” cages and salmon behaviour (Handeland *et al.*, 2003; Johansson *et al.*, 2006; Oppedal *et al.*, 2011). These experiments have used several different *Salmo salar* stocks from Norwegian and UK aquaculture populations, along with a commercially available Aquagen strain (https://aquagen.no/en/, accessed Nov 2018).

An increase in sea water temperature results in an increase in metabolic activity within the fish. Initially, this increases the growth rate of the salmon until and optimum level is reached, after which the growth rate falls (see Figure 10). The growth rate of fish is thus curvilinear and is often described by a second order polynomial. The nature of the temperature performance depends upon the size of the fish and changes as the fish stock matures. The selected optimum level reflects this and the sub-threshold range completes the temperature range over which a positive growth rate is achieved.

Figure 10: Effect of seawater temperature on the growth rate of adult salmon. Taken from (Handeland *et al.*, 2003). SGR is the Specific Growth Rate.



During their life cycle salmon undergo a smoltification process whereby the organism acclimatises to an increase in salinity as they move from freshwater into seawater. The process involves changes in morphology, physiology and behaviour to pre-adapt the fish to the seawater habitat. Smoltification places the organism under hyper-osmotic stress which can restrict growth of the smolts in the sea cages (Handeland *et al.*, 1998).

The environmental thresholds for Atlantic salmon are shown in Table 6 below. Light availability was not considered as growth is affected by photoperiod (day-night) cycles but not by absolute light levels; furthermore, chlorophyll concentration and nutrients were not applicable as phytoplankton is not a food source and not sufficient to provide oxygen for metabolism in a fish farm (Wildish *et al.*, 1993) although there is some evidence that dissolved oxygen levels are affected in the short-term in warm waters (Yoshikawa *et al.*, 2007). TOxN only affects phytoplankton (algae) growth and was therefore not considered.

Table 6: Details of the thresholds chosen for Atlantic salmon (*Salmo salar*) for each environmental variable with references. For details on selection of the threshold parameters see 3.3.1.

Environmental Factor	Optimal	Sub-optimal	Not suitable	References
Minimum SST (°C)	>6	2-6	<2	Jonsson *et al.*, 2001; Larsson and Berglund, 2006; Elliott and Elliott, 2010; Oppedal *et al.*, 2011; Siriwardena, 2018a
Maximum SST (°C)	16-18	<16, 18-22	>22	
Minimum Salinity	22-34	0-22, 35-40	>40	Handeland *et al.*, 1998; Bœuf and Payan, 2001; Boogert *et al.*, 2018; Siriwardena, 2018a
Maximum Salinity	22-34	35-40	>40	
Dissolved Oxygen (mg/L)	>5	3-5	<3	Siriwardena, 2018a

3.3.2 Rainbow trout (*Oncorhynchus mykiss*)

Rainbow trout is a coldwater fish that is native to North America but has been introduced across the globe and can be found across Europe, South America, Australia and parts of Asia and Africa (FAO, 2018e). It is primarily a freshwater species which requires well-oxygenated and unpolluted water to survive. Therefore its natural habitats are fast-flowing rivers or open lakes (FAO, 2018e). Some populations of rainbow trout are migratory, spending a large proportion of their life in seawater (sea-run trout, also known as steelhead trout) and only returning to freshwater to reproduce (Froese and Pauly, 2018). In this report, the optimal conditions for growth in seawater will be considered.

The environmental thresholds for rainbow trout are shown in Table 7 below. As for Atlantic salmon, light, TOxN and chlorophyll layers were not applicable.

Table 7: Details of the thresholds chosen for rainbow trout (*Oncorhynchus mykiss*) for each environmental variable. For details on selection of the threshold parameters see 3.3.2.

Environmental Factor	Optimal	Sub-optimal	Not suitable	References
Minimum SST (°C)	>4	0-4	<0	Elliott and Elliott, 2010
Maximum SST (°C)	12-17	<12, 17-24	>24	
Minimum Salinity	0-24	24-36	>36	McKay and Gjerde, 1985; Boogert *et al.*, 2018; Hardy, 2018
Maximum Salinity	0-24	24-36	>36	
Dissolved Oxygen (mg/L)	>6	6-5	<5	Avkhimovich, 2013; Hardy, 2018

The diet of rainbow trout is mixed and they are opportunist feeders predating on invertebrates, small fish and fish eggs (FAO, 2018e; Hardy, 2018). The sea-run trout appear to grow faster than the freshwater strain, growing 7-10kg over 3 years compared to 4.5kg in freshwater (FAO, 2018e).

Rainbow trout show excellent osmotic regulation and therefore have a broad tolerance range (Froese and Pauly, 2018; Hardy, 2018). Provided the fish are acclimatised then defining an optimum salinity for growth is difficult, however there is some evidence that best growth is obtained outside of full-strength seawater salinities (McKay and Gjerde, 1985).

3.3.3 Brown (sea) trout (*Salmo trutta trutta*)

The native range of *Salmo trutta* includes Europe, northern Africa and western Asia, however, transfer of the species to establish recreational fishing has resulted in the populations of the species occurring across the globe (FAO, 2018f). The brown trout closely resembles Atlantic salmon and rainbow trout in appearance but have a more golden or brown skin colouration. Sea-run brown trout is the anadromous form and typically have a more silvery colouration and the level of spotting below the lateral line is less (FAO, 2018f).

Sea trout commonly refers to the migratory form of brown trout that performs its reproductive cycle in cold freshwater rivers and lakes but spends most of its life at sea. Consequently aquaculture of brown trout has been achieved in both freshwater and marine environments mainly in mainland Europe and the UK (Quillet *et al.*, 1992; Siriwardena, 2018b). In 2010, 80% of brown trout aquaculture was performed in Russia and almost all of this was using freshwater facilities (FAO, 2012). There is a lack of data on the maximum salinity level that brown trout can tolerate. Therefore a value of 40 was taken from Atlantic salmon as an unsuitable salinity level.

The environmental thresholds for brown trout are shown in Table 8 below. As for the other finfish, light, TOxN and chlorophyll layers were not applicable.

Table 8: Details of the thresholds chosen for brown trout (*Salmo trutta trutta*) for each environmental variable. For details on selection of the threshold parameters see 3.3.3.

Environmental Factor	Optimal	Sub-optimal	Not suitable	References
Minimum SST (°C)	>4	0.7-4	<0.7	Solomon and Lightfoot, 2008; Elliott and Elliott, 2010; Siriwardena, 2018b
Maximum SST (°C)	12-17	<12, 17-24	>24	
Minimum Salinity	33–40*	0-33	>40*	Gordon, 1958; Solomon and Lightfoot, 2008; Siriwardena, 2018b
Maximum Salinity	33–40*	0-33	>40*	
Dissolved Oxygen (mg/L)	>6	6-4	<3	Karna, 2003; Avkhimovich, 2013; Siriwardena, 2018b

* - Values estimated from other studies.

Sea trout aquaculture has received attention as an alternative to Atlantic salmon or rainbow trout culture when summer temperatures and salinities are too high (Quillet *et al.*, 1992). In good culture conditions juvenile sea trout (50-350g) can grow to over 2kg after one year at sea (Quillet *et al.*, 1992).

3.3.4 Atlantic cod (*Gadus morhua*)

The Atlantic cod is a voracious and omnivorous finfish species that has a relatively high growth rate, especially in colder waters (FAO, 2018c). It is found in North Atlantic ocean regions and in particular off the coasts of North America, Canada, Greenland, Iceland, Norway, Ireland and the UK (FAO, 2018c). It is generally considered to occupy demersal habitats but can be found in pelagic zones, for example during spawning events (FAO, 2018i).

Atlantic cod has been found in a wide range of cold water temperatures from near freezing to 20°C (Árnason, 2007). Best growth rates are observed between 9°C and 15°C (Björnsson *et al.*, 2001; Björnsson and Steinarsson, 2002, Björnsson *et al.*, 2007). It lives in almost every salinity from nearly fresh to fully oceanic water (Árnason *et al.*, 2013). Salinity appears to have some effect on growth although results are mixed. Lambert *et al.* (1994) showed that a salinity of 7 was better than 28 and Dutil *et al.* (1992) showed 14 as an optimal salinity for growth.

The environmental thresholds for Atlantic cod are shown in Table 9 below. As for the other finfish, light, TOxN and chlorophyll layers were not applicable.

Table 9: Details of the thresholds chosen for Atlantic cod (*Gadus morhua*) for each environmental variable. For details on selection of the threshold parameters see 3.3.4.

Environmental Factor	Optimal	Sub-optimal	Not suitable	References
Minimum SST (°C)	>4	0-4	<0	Árnason, 2007; Solomon and Lightfoot, 2008; Elliott and Elliott, 2010; Freitas *et al.*, 2015
Maximum SST (°C)	12-17	<12, 17-24	>24	
Minimum Salinity	0-24	24-36	>36	Dutil *et al.*, 1992; Lambert *et al.*, 1994; Árnason *et al.*, 2013; Boogert *et al.*, 2018
Maximum Salinity	0-24	24-36	>36	
Dissolved Oxygen (mg/L)	>6	6-5	<5	Kiceniuk and Colbourne, 1997; Karna, 2003

The Atlantic cod is one of the most important commercial fishes and at its peak (1968) almost 4 million tonnes was caught (FAO, 2018c). However, cod stocks have suffered massively and catch tonnage has dropped significantly since 2000 reaching a low of 770,500 tonnes in 2008 (FAO, 2018c). At present Atlantic cod has a “vulnerable” status on the IUCN Red list.

High demand and reduced supply have led to development of aquaculture of Atlantic cod. Aquaculture production peaked around 2010 at nearly 25 thousand tonnes but has since declined to 509 tonnes in 2016 (FAO, 2018g). A major issue has been a bottleneck in the production of juvenile fish for growing on to adult harvest in sea cages (sea cages similar to those used for salmon). Typical aquaculture of cod takes 24-36 months after hatching to harvest (FAO, 2018b).

3.4 Crustacean

For the crustacean species the following environmental variables were considered:

- Sea surface temperature
- Salinity
- Dissolved Oxygen Concentration.

3.4.1 European lobster (*Homarus gammarus*)

The European lobster can be found from Scandinavia to North Africa and their natural habitat is solitary shelters in rocky substrates (FAO, 2018h). They feed mainly on benthic invertebrates, preying on small crustaceans, molluscs and polychaetes. Growth is achieved by moulting which occurs approximately every summer for adults (Cefas Shellfish Team, 2017b).

There is a strong correlation between water temperature and growth and Lewis (2002) showed that reduced temperatures resulted in reduced growth rates. In addition to the absolute temperature, fluctuating temperatures can cause stress and also reduce growth.

Marine crustaceans, such as the European Lobster have a blood composition that has the same overall concentration of osmotically active particles as that of seawater (Lucu and Devescovi, 1999). Although they are able to adjust to changes in external salinity by actively altering their blood protein and ion concentration to maintain isosmotic internal conditions the European lobster is a stenohaline species (Lucu and Devescovi, 1999; Laing, 2002). Typically, a reduction in salinity below standard seawater results in a reduction in the growth rate of the lobster (Beard and McGregor, 2004; Bignell *et al.*, 2016).

Flow through an aquaculture system delivers oxygenated water to the individuals and also removes waste products produced. Recommended flow rates for rearing lobsters are between 4l/min to 100l/min (Drengstig and Bergheim, 2013). Low flow rates can result in decreased dissolved oxygen concentration because there is a lack of turnover of water in the culture. Furthermore, accumulated waste products are broken down by decomposing bacteria further reducing oxygen levels in the water. Too high flow rates can cause stress to the animals. A review of flow requirements by Halswell *et al.* (2018) suggested rates below 0.1m/s altered feeding behaviour and above 0.27m/s affected olfactory behaviour.

The environmental thresholds for European lobster are shown in Table 10 below. Light availability is not considered as no information was available for *Homarus gammarus* (although photoperiod has been shown to affect larval development in *Homarus americanus;* Bignell *et al.*, 2016). Furthermore, chlorophyll concentration and TOxN are also not relevant as lobsters are carnivorous and do not feed on plankton.

Table 10: Details of the thresholds chosen for European lobster (*Homarus gammarus*) for each environmental variable with references. For details on selection of the threshold parameters see 3.4.1

Environmental Factor	Optimal	Sub-optimal	Not suitable	References
Minimum SST (°C)	>5	0 - 5	<0	Bignell *et al.*, 2016
Maximum SST (°C)	10-22	<10, 22-31	>31	
Minimum Salinity	32	8 - 32	<8	Beard and McGregor, 2004; Bignell *et al.*, 2016
Maximum Salinity	32	32 - 46	>46	
Dissolved Oxygen (mg/L)	>6.2	4.5 - 6.2	<4.5	Beard and McGregor, 2004;

3.5 Bivalves molluscs

For the bivalve mollusc species the following environmental variables were considered:

- Sea surface temperature
- Salinity
- Dissolved Oxygen Concentration
- Chlorophyll concentration.

The bivalves (class Bivalvia) are molluscs (phylum Mollusca) that have a shell of two-valves that have a dorsal hinge and are held together by a tough elastic ligament (McNeill Alexander, 1990). The class includes the families Mytilidae (mussels), Ostreidae (oysters), Veneridae (clams) and Pectinidae (scallops). Bivalves are common members of the intertidal fauna and live attached to rocky shores or buried in loose sediments (Leal, 2018). As filter feeders they obtain their nutrition by extracting microscopic algae (phytoplankton) and organic detritus from sea water. To achieve this, active suspension feeders pull sea water into the bivalve, either directly onto the gills, or through a siphon first in buried species, to remove oxygen and then through the intestines to remove food (Kooijman, 2006). Contaminated sediment is usually removed before entry into the intestine and passes out as pseudo-faeces (McNeill Alexander, 1990; Kooijman, 2006). Particulate matter in the water (seston), can vary greatly, containing different sediment particle sizes and different phytoplankton species. However, the influence seston has on bivalve growth is strongly correlated to environmental conditions (Bayne, 1998).

Sea water temperature has a major effect on the seasonal growth of bivalves and may be responsible for much of the difference in growth observed between sites (Laing and Spencer, 2006). Around the UK, growth of bivalves usually occurs when temperatures reach 8-9°C with fastest growth occurring when the temperatures reach a peak of 16-18°C in the summer months (Laing and Spencer, 2006). Laboratory and field experiments suggest that bivalves can survive temperatures above 25°C but that temperatures above 20°C are harmful causing stress to the animals and an increase in mortality (Laing and Spencer, 2006). Mussels appear to be tolerant of very low temperatures but other bivalves such as scallop and clam may experience mortality if the temperature goes below 5°C (Laing and Spencer, 2006).

Because the bivalve obtains nutrition from phytoplankton (containing chlorophyll) and from organic detritus (absent of chlorophyll) it is difficult to have a robust link between chlorophyll levels and minimum food rations (Cranford *et al.*, 2011). In field observations, food availability shows large spatial and temporal variation (Pieterse, 2013). The range of seston quality and quantity at coastal sites varies from 3 to 100mg of Suspended Particulate Matter per litre (SPM/L) of which 5-80% may be organic (Jorgensen, 1996; Chronis *et al.*, 2000; Szostek *et al.*, 2013). However, bivalves are also found in “low-seston environment” sites with seston levels below 1mg SPM/L and chlorophyll levels below 1.5µg/L (Rosland *et al.*, 2009). The difficulty in obtaining a good association between chlorophyll levels as a proxy for food ration and growth and condition of bivalves is well documented (e.g. Flyte *et al.*, 2007) and optimal and suboptimal levels for bivalves have yet to be confirmed. Therefore, in this report a minimum level of chlorophyll concentration will be used.

As euryhaline species, bivalves often naturally experience changes in salinity and they are therefore, in general, tolerant of salinity fluctuations (Laing and Spencer, 2006). Such natural changes occur in estuarine regions due to influxes of freshwater from rivers, or from stratification of the water under heavy rainfall in the intertidal zone (Pauley *et al.*, 1988; Laing and Spencer, 2006; Nel *et al.*, 2014). These changes are typically temporary, and bivalves tend to suffer little mortality because of it (Laing and Spencer, 2006) but instances of summer mortalities linked to tidal influences have been documented (Cheney *et al.*, 2000) but have not been associated with salinity changes.

In nature the growth and mortality of bivalves is affected by intra-specific and inter-specific competition, predation and disease (Spencer, 1990; OSPAR, 2009). The nature of the aquaculture process serves to control intra-specific competition through good stocking density practices. Typical aquaculture methods for bivalves ensure that they are continually fully submerged and not in contact with the substrate. This reduces inter-specific competition and predation through isolation of the stock (Spencer, 1990; Laing and Spencer, 2006). Although they can be significant the effect of disease is not covered in this report.

3.5.1 Pacific oyster (*Crassostrea gigas*)

The Pacific oyster (*Crassostrea gigas*) is a euryhaline, bivalve native to Japan but has been widely introduced as a cultivated species across the United States of America and into Europe (reviewed in FAO, 2004). Naturally it is an estuarine species occupying the lower intertidal zone down to depths of 40m. Populations of the Pacific oyster may therefore be fully submerged or experience a twice-daily exposure to the air. There is some evidence that sub-populations of *Crassostrea gigas* in sub-tidal or intertidal areas respond differently to salinity changes (Yang *et al.*, 2016) however it is generally understood that environmental factors have a greater effect on growth characteristics and not any underlying genetic differences (see Evans and Langdon, 2006).

Spencer (1990) has shown that exposure to air (measured as a percentage of the total time exposed) is tolerated as adults by closing the shell, but that the juveniles (spat) can only tolerate 25-35% time exposure to air. Growth is optimal at 0% exposure to the air and therefore complete immersion is the optimal condition for cultivation. However, exposing the spat to the air has been routinely used as a method of slowing down growth of oyster stock (known as hardening-off the spat) and provided the air temperature is not too high then mortality at exposure levels above 34% is low (Laing and Spencer, 2006). The ability to tolerate air exposure is achieved by the oyster closing its shell and adopting an anaerobic metabolism which ultimately halts growth and can lead to mortality (Allen and Burnett, 2008). For this study the dissolved oxygen parameters are based on growth during immersion in the seawater and the unsuitable level refers to prolonged immersion at this level.

Published data on the effect of environmental variables on the growth of the Pacific oyster focus on the reproductive (gametogenesis), larval and adult phases (Brown, 1986; Chávez-Villalba *et al.*, 2002; Dégremont *et al.*, 2005; Pieterse, 2013). The optimal values are different between these phases and for the naturally available populations the realised niche may be optimal for just one of these phases. This is especially true for gametogenesis (egg production) which can be temperature-limited but can be controlled by the culture of sterile or semi-sterile individuals (Shpigel *et al.*, 1992; Chávez-Villalba *et al.*, 2002). An increase in water temperature can increase the probability of gametogenesis which results in a decrease in growth rate as resources are directed into gamete formation (Shpigel *et al.*, 1992). A meta-data analysis study by Wadsworth *et al.* (2019) has concluded that triploid oysters have a 49% increase in growth rate compared to their natural diploid state; although there were some studies in their meta-data analysis that showed no advantage. In addition, the growth of the Pacific oyster in the sub-tidal zone is increased in comparison to cultivation in the inter-tidal zone (Evans and Langdon, 2006). This is due to a reduction in the metabolic rate of these oysters when faced with the twice-daily anoxic environment caused by air exposure (Laing and Spencer, 2006).

Pacific oysters are suspension feeders that obtain their nutrition from food particles suspended in the water column. Water is siphoned into the oyster and particle selection occurs at the gills (McNeill Alexander, 1990; Kooijman, 2006; Pieterse, 2013). Oysters prefer seston (living and non-living particulate matter) that is rich in small diatoms and flagellates and poor in harmful algae and detritus (Baldwin and Newell, 1995). The effect of phytoplankton levels on the growth of the Pacific oyster is mixed. Most studies have shown a significant positive effect of phytoplankton composition and concentration on growth (for example, King *et al.* 2006, Pieterse, 2013) and that best growth is achieved when oysters are held close to the surface where food supply is abundant. Others have reported lower growth at the surface (for example Toro *et al.*, 1999). The situation is more complicated when inorganic suspended particles are present with some studies suggesting that feeding stops above 200g/L for oysters (Jorgensen, 1996; Gernez *et al.*, 2014).

In summary, the environmental factors influencing potential Pacific oyster cultivation could be influenced by the stage in the life cycle employed, the habitat that the oyster will be cultivated in, and whether semi-sterile or sterile juveniles will be grown on. In this study the environmental thresholds were obtained for larval and adult Pacific oysters.

The effect of environmental drivers on disease in oysters is well established (King *et al.*, 2018) but is not considered here.

The environmental thresholds for Pacific oyster are shown in Table 11 below. Light availability and TOxN were not considered as they do not affect growth of *Crassostrea gigas*. Nutrient and light affect phytoplankton levels which is assessed by the chlorophyll suitability factor.

Table 11: Details of the thresholds chosen for Pacific oyster (*Crassostrea gigas*) for each environmental variable. For details on selection of the threshold parameters see 3.5.1.

Environmental Factor	Optimal	Sub-optimal	Not suitable	References
Minimum SST (°C)	>15	4-15	<4	Pauley *et al.*, 1988; Franco, 2017; FAO, 2018i
Maximum SST (°C)	15-25	<15, 25-35	>35	
Minimum Salinity	>20	13-20	<13	Pauley *et al.*, 1988; Laing and Spencer, 2006; FAO, 2018i, Goulletquer, 2018
Maximum Salinity	25-35	20-25, 35-40	>45	
Chlorophyll (µg/L)	>8	1-8	<1	Brown, 1986; Bourlès *et al.*, 2009
Dissolved Oxygen (mg/L)	>8	4.5-8	<4.5	Goulletquer, 2018

3.5.2 Native oyster (*Ostrea edulis*)

The native oyster (also known as the European flat oyster) has been used as a food source in Europe for many centuries. It is a euryhaline species able to inhabit inshore waters and estuaries and can therefore be cultivated under a wide range of conditions (Korringa, 1952; Laing and Spencer, 2006). It is, however, less tolerant of sedimentation than the Pacific oyster and has been out-competed by this species in many parts of Europe (Gosling, 2003). At the end of the nineteenth century *Ostrea edulis* experienced a massive decline in oyster fisheries across Europe. Initial attempts to rectify this introduced new diseases and predators which accelerated the decline in flat oyster stocks (Gosling, 2003; Roberts, 2018b).

As a benthic filter feeder, the native oyster can gain nutrition from a mixed diet of phytoplankton and organic matter suspended in the water. The prevailing view is that filtration rate is autonomous and dependent on the level of suspended particulate matter and that selective filtration based on size or other particle characteristics is based on the system rather than controlled by the organism (Jorgensen, 1996). However, specific particle selection was suggested by Shumway *et al.* (1985) who showed that *Ostrea edulis* is able to select, or at least filter, some phytoplankton better than others. Hutchinson and Hawkins (1992) reported that filtration was completely inhibited by 10mg/L of particulate organic matter and significantly reduced by 5mg/L suggesting that *Ostrea edulis* is intolerant of turbid (silt laden) environments.

In the field, feeding ration rarely is limiting and water temperature has the major influence on the oyster's growth and reproduction, being linked to spawning (Perry and Jackson, 2017) and growth (Haure *et al.*, 1998). Under suitable conditions, growth is rapid for the first year and a half before slowing to 20g per year for another 5 years before reducing again (Perry and Jackson, 2018). Best production potential for *Ostrea edulis* appears to be between 15°C and 25°C when energy input from filter-feeding is relatively high and balanced by the increased in respiratory losses as the metabolic rate increases (Hutchinson and Hawkins, 1992; Perry and Jackson, 2017). Growth rates of *Ostrea edulis* are faster in sheltered sites than exposed locations and therefore they tend to be found in areas with very weak or weak (<0.5m/sec) tidal flows (Perry and Jackson, 2017). These conditions are believed to deliver higher seston volumes rather affect growth through changes in filtration flow rates or food availability (Valero, 2006; Perry and Jackson, 2017).

High population densities and inter-specific competition from introduced species such as the slipper limpet impacts on the growth of *Ostrea edulis* (Laing and Spencer, 2006). In addition, natural predators such as starfish, winkles and whelk will reduce population sizes (Laing and Spencer, 2006). In recent times the most influential cause of population crises has been the spread of the protozoan parasite *Bonamia ostreae*. This parasite has caused mass population crashes significantly reducing the stock of *Ostrea edulis* across Europe (see Laing and Spencer, 2006; OSPAR, 2009; Fariñas-Franco *et al.*, 2018).

The environmental thresholds for native oyster are shown in Table 12 below. Light availability and TOxN were not considered as they do not affect growth of *Ostrea edulis*. Nutrient and light affect phytoplankton levels which is assessed by the chlorophyll suitability factor.

Table 12: Details of the thresholds chosen for native oyster (*Ostrea edulis*) for each environmental variable. For details on selection of the threshold parameters see 3.5.2.

Environmental Factor	Optimal	Sub-optimal	Not suitable	References
Minimum SST (°C)	>10	-1-10	<-1	Walne, 1958; Haure *et al.*, 1998; Laing and Spencer, 2006
Maximum SST (°C)	12-20	10-12, 20-25	>25	
Minimum Salinity	>25	15-25	<15	Laing and Spencer, 2006; FAO, 2018j
Maximum Salinity	25-35	20-25, 35-40	>40	
Chlorophyll (µg/L)	>8	1-8	<1	Values used from Pacific oyster
Dissolved Oxygen (mg/L)	>8	4.5-8	<4.5	Values used from Pacific oyster

Occupying sub-tidal and intertidal zones the native oyster has adapted to tolerate short periods of air exposure. As a suspension feeder periods of air-exposure reduce the time over which feeding can occur and therefore full immersion is preferential in aquaculture (Laing and Spencer, 2006). However, *Ostrea edulis* can tolerate air exposure up to 35% above which growth of the oyster stops (Laing and Spencer, 2006).

3.5.3 Blue mussel (*Mytilus edulis*)

The blue mussel (*Mytilus edulis*) has a long history of harvest and aquaculture and is widely distributed in European waters due to its ability to withstand wide fluctuations in salinity, desiccation, temperature and oxygen availability (FAO, 2018k). They are present in marine and brackish waters occupying high intertidal to sub-tidal regions in estuarine and oceanic locations. In aquaculture the blue mussel thrives in sub-tidal areas suggesting that predation limits its realised niche and not environmental factors (FAO, 2018k). Although they can live for up to 24 years, a typical mussel is harvested after less than 2 years in culture (FAO, 2018k).

As with most marine ectotherms, the environmental factor that has the biggest effect on growth and survival of the blue mussel is temperature (Dare, 1980). *Mytilus edulis* is more tolerant to extremes of temperature and can survive freezing temperatures of up to -10°C (Jahn *et al.*, 1992) and even shows small levels of growth even at -1°C (FAO, 2018l). This allows the species to survive and thrive in intertidal regions that have daily exposure and therefore potentially large changes in temperature (for review see Zippay and Helmuth (2012)). In aquaculture however the mussels are typically cultured immersed on ropes or in trays and therefore in this report the sea surface temperature will be used as the determining factor for growth.

An intertidal existence can also result in daily changes in salinity. Influx of freshwater from rivers or rain can dilute the seawater or stratify the water column into an increasing salinity with depth. In general, mussels have been shown to have a decreased growth rate with decreased salinity (Dare, 1980). As a euryhaline organism they can tolerate a wide range of salinities, down to 4, however they are less stressed under higher saline conditions (Riisgård *et al.*, 2012; Franco, 2017) and prefer salinities above 18 (FAO, 2018l). Decreased salinity levels result in a reduction in the time that the mussel opens its valve. This in turn reduces feeding and therefore impacts on potential growth (Laing and Spencer, 2006; Riisgård *et al.*, 2012).

Mussel filtration rate is also dependent on water turbidity. Mussels feed mainly on phytoplankton and this appears to be their preferred food source (Riisgård *et al.*, 2011). However, they will also feed on organic detritus, but this is a relatively poor source of nutrition. In response to both a high water turbidity and a low water turbidity the blue mussel closes its valve and the filtration rate reduced (Riisgård *et al.*, 2011). At high levels of turbidity this prevents overloading of the intestinal space with inorganic particles that may be in the seston. Prior to the upper threshold undigested particles are removed by the production of pseudofaeces which reduces the level of overall digestion and therefore growth (Kooijman, 2006; Crandford *et al.*, 2011; Steeves *et al.*, 2018).

Current thinking is that filtration rate remains maximal between an upper and lower threshold of food availability (Riisgård *et al.*, 2011; Strand *et al.*, 2016; Steeves *et al.*, 2018). This is autonomously regulated and these thresholds differ according to the algal cells, organic matter and inorganic matter present. Too much turbidity and the intestine becomes over-burdened and too little means the digestive effort exceeds the energy obtained. The seston concentration at which mussels start feeding has been estimated to be between 0.5 and 1µg/L from laboratory and field studies (Strohmeier, 2008).

Wind has strong effect on mussel growth as it is a prime driver of the resuspension of material due to wave action. This is particularly true in shallow waters that are often used for mussel farming (Filgueira *et al.*, 2018). It is therefore clear that any national suitability score for mussel farming should then be subjected to local parameters to ensure sufficient shelter for the mussel farm (Laing and Spencer, 2006). It is recommended that a dynamic energy budget model is generated using existing approaches but locally derived parameters, such as Larsen and Riisgård (2016). This will further demonstrate feasibility.

The environmental thresholds for blue mussel are shown in Table 13 below. Light availability and TOxN were not considered as they do not affect growth of *Mytilus edulis*. Nutrient and light affect phytoplankton levels which is assessed by the chlorophyll suitability factor.

Table 13: Details of the thresholds chosen for blue mussel (*Mytilus edulis*) for each environmental variable. For details on selection of the threshold parameters see 3.5.3.

Environmental Factor	Optimal	Sub-optimal	Not suitable	References
Minimum SST (°C)	>8	-4-8	<-4	Lauzon-Guay *et al.*, 2006; Zippay and Helmuth, 2012; Franco, 2017; FAO, 2018l; Stevens and Gobler, 2018
Maximum SST (°C)	12–17	8-12, 12-25	>25	
Minimum Salinity	>18	4-18	<4	Fisher, 1986; Laing and Spencer, 2006; Riisgård *et al.*, 2012; Franco, 2017
Maximum Salinity	25-30	18-25, 30-40	>40	
Chlorophyll (µg/L)	>6	1-6	<1	Riisgård *et al.*, 2011
Dissolved Oxygen (mg/L)	>7	1.5-7	<1.5	Bergström and Lindegarth, 2016

3.5.4 Manila clam (*Ruditapes philippinarum*)

The Manila clam (*Ruditapes philippinarum*) is a marine bivalve mollusc that is indigenous to sub-tropical and temperate coastal seas (for review see Yang *et al.*, (2018)). It originates from South-East Asia where its natural habitat is sheltered sites at 1-10m depth of water, usually below mid-tide level and in littoral lagoons and estuaries. The Manila clam can live buried in a range of substrates including sandy, sandy-mud and muddy substrates (Uddin *et al.*, 2013) where it inhabits the top 10cm of the substrate, its depth being limited by the length of its siphon (Kasai *et al.*, 2004). Cultivation of the clam across the world has considerably extended its range and naturalised populations are found in USA and Canada, the Mediterranean and the Atlantic coast of Europe (Chiesa *et al.*, 2017; Cordero *et al.*, 2017; FAO, 2018d).

The clam has two equally sized shells of height 19-31mm, width 13-22mm and a length distribution of 25-57mm in naturalised populations in Europe and maximum length of 80mm (Harris, 2016). Manila clam has at least 17 common names such as the carpet shell clam, the Japanese carpet shell and mud clam. It also has a volatile history of taxonomical reclassification with at least 28 scientific binomial names including *Ruditapes philippinarum*, *Tapes philippinarum*, *Tapes japonica* and *Venus philippinarum* (FAO, 2018d; Humphreys and Yang, 2018). In this report the scientific name *Ruditapes philippinarum* and the common name Manila clam will be used (following the taxonomy as described in the World Register of Marine Species[2]).

Although naturally occupying intertidal niches the long-term exposure to the air results in organism stress and the use of less efficient anaerobic metabolism (Yin *et al.*, 2017). Laboratory and field studies have shown that longer air-exposure results in a decrease in survival and growth rate (Yin *et al.*, 2017). Furthermore, Laing and Spencer (2006) report that 50% exposure to air stops growth completely. These are important implications for siting Manila clam aquaculture.

The diet of the Manila clam is mainly phytoplankton and therefore its concentration in the water can be a significant limiting factor on the growth of the clam. The adult clams will also feed on zooplankton and particulate organic matter in the water. Kang *et al.* (2016) estimate the optimum suspended particulate matter to be 100-200mg/L at 18°C. To ensure sufficient water passes into the clam a tidal flow of 50-100cm/s is optimal, with a suboptimal tolerance down to 25cm/s (Seafish, 2019a) although some authors have claimed high clearance rates at lower velocities (Sobral and Widdows, 2000). Outside of its optimal salinity the Manila clam will stop filter-feeding and therefore its growth rate declines (Kim *et al.*, 2001). Estimating the food availability in the water column is a difficult process for benthic filter feeders because of their varied diet (Kasai *et al.*, 2004). Chlorophyll is often used as a proxy for phytoplankton concentrations in the water however a study by Flye-Sainte-Marie *et al.* (2007) revealed that this was not a good estimator for benthic suspension feeders.

The success of *Ruditapes philippinarum* in the colonisation of many habitats around the world is in large part due to its physiological plasticity (Beninger and Lucas, 1984; Laing *et al.*, 1987; Cordero *et al.*, 2017; Humphreys and Yang, 2018). It is able to adjust physiological processes to balance its energy budget and therefore out-perform competitors in the intertidal zone. An example of this is the compensatory effects of temperature and filter-feeding rates (Kang *et al.*, 2016). As an ectotherm, an increase in water temperature will increase metabolic activity and therefore metabolic energy losses increase (Schulte, 2015). To compensate the clam increases its filtration rate (Kang *et al.*, 2016) thereby allowing the organism to survive in a greater range of water temperatures.

Ruditapes philippinarum has recently been introduced into the UK for aquaculture and its naturalisation and dispersal along the South coast estuaries has been studied (see Harris, 2016). This gives an insight into possible environmental field conditions that are important for the survival and growth of the clam. *In situ* studies are

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[2] www.marinespecies.org/aphia.php?p=taxdetails&id=231750

inherently difficult to use to isolate environmental factors due to temporal fluctuations between sites and differences in food sources and predation.

A typical harvest will take 2 to 3 years for the clams to leave the hatchery and grow to market size. During this time there is the possibility of at least one spawning event occurring (FAO, 2018d). In other bivalves such as the Pacific oyster (*Crassostrea gigas*) there is a link between reproduction and a decreased growth rate (see Section 3.5.1). In this case the use of sterile populations in aquaculture appears to improve growth rate and efficiency. In the Manila clam, however, studies have yet to show a positive effect of using sterile organisms. For example, Shpigel and Spencer (1996) did not show any significant effect of gametogenesis on the growth rate of diploid clams versus triploid (sterile) clams.

The environmental thresholds for Manila clam are shown in Table 14 below. Light availability and TOxN were not considered as they do not affect growth of *Ruditapes philippinarum*. Nutrient and light affect phytoplankton levels which is assessed by the chlorophyll suitability factor.

Table 14: Details of the thresholds chosen for Manila clam (*Ruditapes philippinarum*) for each environmental variable. For details on selection of the threshold parameters see 3.5.4.

Environmental Factor	Optimal	Sub-optimal	Unsuitable	References
Minimum SST (°C)	>5		<5	Spencer *et al.*, 1991; Harris, 2016; Kang *et al.*, 2016; Franco, 2017; Humphreys and Yang, 2018
Maximum SST (°C)	18-23	5-18, 23-30	>30	
Minimum Salinity	>25	12-25	<12	Franco, 2017; Humphreys and Yang, 2018
Maximum Salinity	25-35	12-25, 35-40	>40	
Chlorophyll (µg/L)	>2	2-1	<1	Vincenzi *et al.*, 2006; Flye-Sainte-Marie, *et al.*, 2007
Dissolved Oxygen (mg/L)	>8	1.1-8	<1.1	Kim *et al.*, 2001; Carter, 2003

3.5.5 King scallop (*Pecten maximus*)

The king scallop (also known as Great Atlantic Scallop or Atlantic Scallop) is a benthic bivalve which prefers substrates of clean firm sand, fine gravel or sandy gravel (Laing, 2002). It is adapted to a life in temperate to cold regions and its natural habitat is sub-tidal with relatively constant temperature, salinity and food levels (Marshall and Wilson, 2008). King scallops are less well adapted to large environmental variations compared to other bivalves such as clams (see Section 3.5.4) and oysters (see Sections 3.5.1 and 3.5.2).

In aquaculture, scallop seed is grown-on in pearl and lantern nets (Laing, 2002). These are suspended from long-lines and therefore the scallop does not experience the same conditions as in the wild. Although growth of scallop in these situations is largely similar (Laing, 2002), wave action and the corresponding net movement can cause scallop stress and therefore reduce the growth rate. The effectiveness of the grow-on process is both site and growth-system dependent (see Christophersen and Strand, 2003). Spat can be transferred to sea at a shell-height of around 2mm, however this can be fatal if the sea temperature is below 7°C (Christophersen, 2005). This report will consider growth optima for larger spat and adult scallops.

The king scallop grows best in water with a salinity between 30 and 35 (Laing, 2002). As with other bivalves the tolerance is affected by the temperature of the seawater (Laing, 2002). Although king scallop will tolerate salinity levels down to 26 their growth rate will be reduced. Lower salinity is stressful to king scallops (Laing and Spencer, 2006). They can tolerate short-term exposure to low salinities around 20 but this increases mortality rates, especially at lower temperatures (Strand *et al.*, 1993; Franco, 2017). For example, at 10°C mortality was 100% when exposed to 20 for 6 hours per day for 3 days (Christophersen, 2005). It is therefore important to consider the local salinity and temperature profiles for any site. For this report, lower salinities are considered unsuitable.

Unlike other bivalves, the king scallop is unable to close the aperture completely when exposed to air (Wildish *et al.*, 1992; Strand *et al.*, 2016). Therefore, king scallop needs to be fully submerged during cultivation as any air exposure will result in desiccation. Sites with a water depth of at least 15m are ideal for suspension cultures. To prevent salinity changes due to rainwater mixing it is better to avoid culture in the top 1-2m of the water column. Suspending below 2m but still in near surface waters would allow benefits from increased water temperature while the increased water depth increases the gap between the bottom of suspended culture and the seabed offering reduced predator effects (Laing, 2002; Strand *et al.*, 2016).

As a benthic filter feeder the king scallop feeds mainly on phytoplankton but also some organic detritus. Field studies have estimated that 85% of the difference in growth rates between sites is due to differences in temperature and primary productivity (Laing, 2002). A correlation between spat growth and the concentration of chlorophyll in sea water has been revealed (Laing, 2000). Further, it appears that adult scallops consistently obtain food rations above that needed for maximum growth (Laing, 2002). Filtration rate can be altered in response to changes in food availability and food quality. However, if the water becomes too turbid filtration, and therefore feeding, ceases (Wildish *et al.*, 1992). This should be considered in view of algal blooms when turbidity can exceed 200 cells/µl (4.25mg organic weight/L) and exceed this upper limit (Laing, 2004). Further, field and laboratory studies indicate that the primary driver of scallop spat growth is the water temperature and food availability is rarely limiting (Laing, 2000).

Like other marine bivalves, *Pecten maximus* is a poor oxy-regulator (Artigaud *et al.*, 2014) and therefore changes in dissolved oxygen levels will be important over long-term exposures. A study by Artigaud *et al.* (2014) investigated the effects of temperature and dissolved oxygen concentration on the respiration rates of adult scallops. These results showed a depressed respiration at 10°C and 25°C compared to 18°C. Further, a decline in the respiration rate was observed at around 50% oxygen saturation at 18°C and therefore this will be used as a boundary for the sub-threshold level. At oxygen saturation levels between 10 and 20%, respiration rates were significantly reduced for all three temperatures (Artigaud *et al.*, 2014).

The environmental thresholds for King scallop are shown in Table 15 below. Light availability and TOxN were not considered as they do not affect growth of *Pecten maximus*. Nutrient and light affect phytoplankton levels which is assessed by the chlorophyll suitability factor.

Table 15: Details of the thresholds chosen for King scallop (*Pecten maximus*) for each environmental variable with references. For details on selection of the threshold parameters see 3.5.5.

Environmental Factor	Optimal	Sub-optimal	Not suitable	References
Minimum SST (°C)	>10	6–10	<6	Laing, 2002; Artigaud *et al.*, 2014; Franco, 2017
Maximum SST (°C)	10–17	17-25	>25	
Minimum Salinity	30-35	29-30, 35-40	<29	Laing, 2002; Franco, 2017
Maximum Salinity	30-35	29-30, 35-40	>40	
Chlorophyll (µg/L)	<20	1-20	>1	Laing, 2002
Dissolved Oxygen (mg/L)	>8	2–8	<2	Artigaud *et al.*, 2014

4 Aquaculture potential assessment results

4.1 Environmental data layers used in the study

The lowest sea surface temperatures were observed off the East Anglia coast (particularly around the Wash, 4ºC), and the central North Sea, while areas off the Cornish coast, Isles of Scilly and Celtic Sea presented the highest minimum temperatures, with over 8ºC (Figure 11). While the maximum sea temperature reached highest values off the Thames estuary (around 18ºC), and the Celtic Sea, with lower values off the East coast, north of the Humber (<16ºC; Figure 11). The maximum sea surface temperature ranged from 14.7°C to 19°C and the minimum sea surface temperature ranged from 3.9°C to 11.1°C.

Lowest salinity was recorded in coincidence with the outflow of major rivers such as the Severn, the Thames, the Wash, the Tyne, and in Morecambe Bay (Figure 12); in contrast sea areas around the Isles of Scilly and the Cornish peninsula presented the highest minimum salinity, likely as result of the influence of Atlantic waters (Figure 12). The minimum salinity ranged from 0.01 to 35.6 and the maximum salinity from 24.2 to 36.0.

Mean dissolved oxygen was highest around the south west coast and in the Celtic Sea, in the offshore area of Liverpool Bay, and in patches in the North Sea (Figure 13). The level of dissolved oxygen ranges from 6.8mg/L to 10.6mg/L within the expected values given the sea temperatures and salinity.

The depth of the 10% surface irradiance in spring (Figure 13) ranged between 1m off the Thames estuary to almost 20m in the clear waters of the Celtic Sea, at the shelf edge (Figure 13). Other areas, with reduced light penetration through the water column (higher turbidity) were observed in the Bristol Channel, between the Humber and Wash, around the Isle of Wight, in Liverpool Bay and Morecambe Bay (Figure 13). Areas off the East coast, north of Flamborough, showed an average depth of 10% surface irradiance of approximately 10m, indicating lower levels of turbidity, compared to the southern part of the English East coast (Figure 13). The range of light penetration depths is from 0.7m to 18.7m.

The Total Oxidised Nitrogen (TOxN) concentration was highest at the estuaries of major rivers (e.g. Thames, Severn, Wash, Humber), and generally low off the North-East coast of England, central North Sea and in the South-West (Figure 14). The TOxN concentration ranged from 2.5mM to 479mM.

Chlorophyll concentration was generally higher in coastal areas, off East Anglia, the Wash, Liverpool Bay and in the Western English Channel, offshore the coast of Cornwall (Figure 14). This layer serves as a proxy for the level of primary productivity in the water and ranged from 0.14 mg/L to 34.0 mg/L.

Figure 11: Maximum (a) and minimum (b) sea surface temperature experienced in the English Economic Exclusion Zone. The maximum is the 97.5th percentile and the minimum is the 2.5th percentile of daily temperature readings from 2006 to 2014 (see 2.3.1)

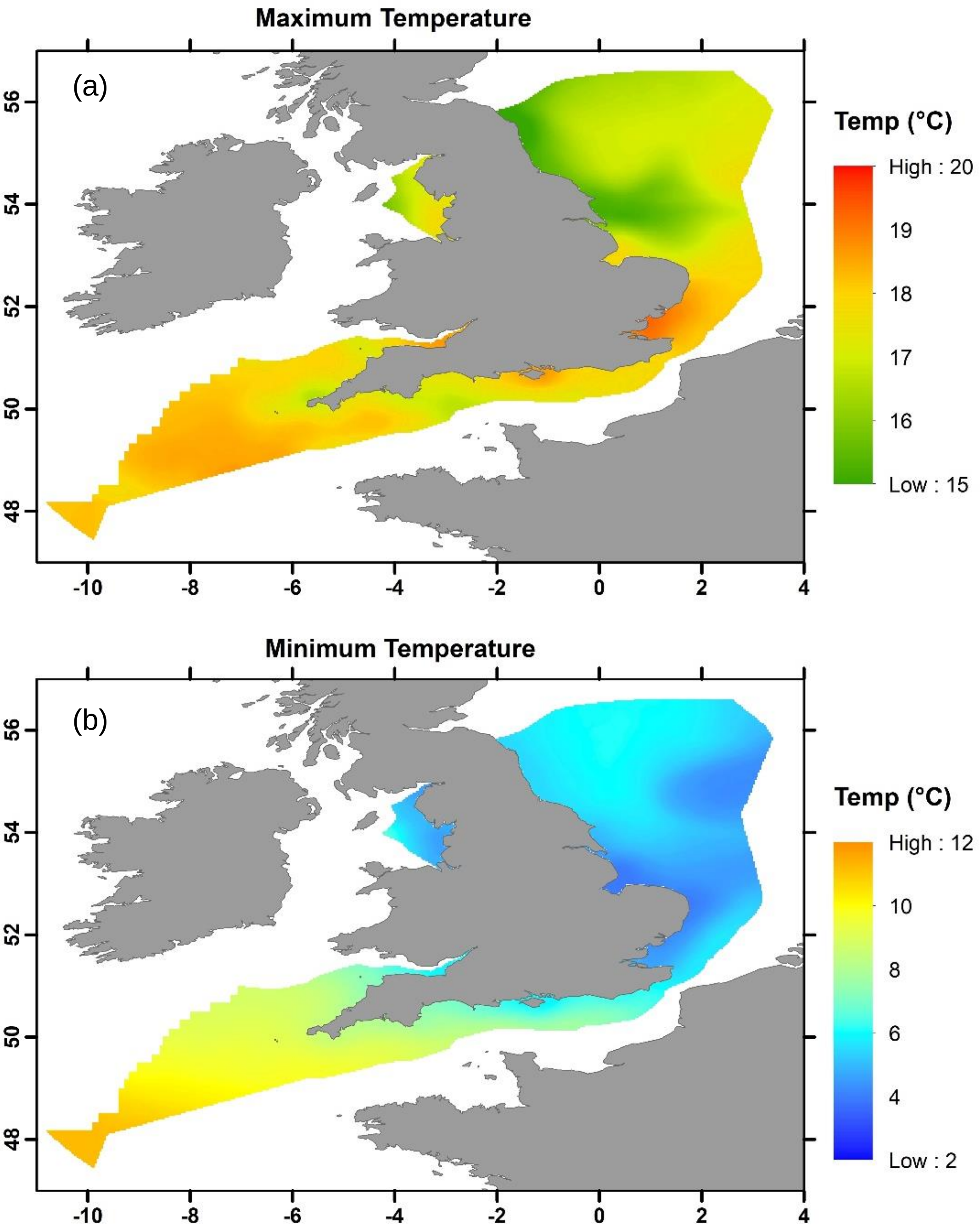


Figure 12: Maximum (a) and minimum (b) salinity experienced in the English Economic Exclusion Zone. The maximum is the 97.5th percentile and the minimum is the 2.5th percentile of in situ salinity readings from 2000 to 2014 (see 2.3.2)

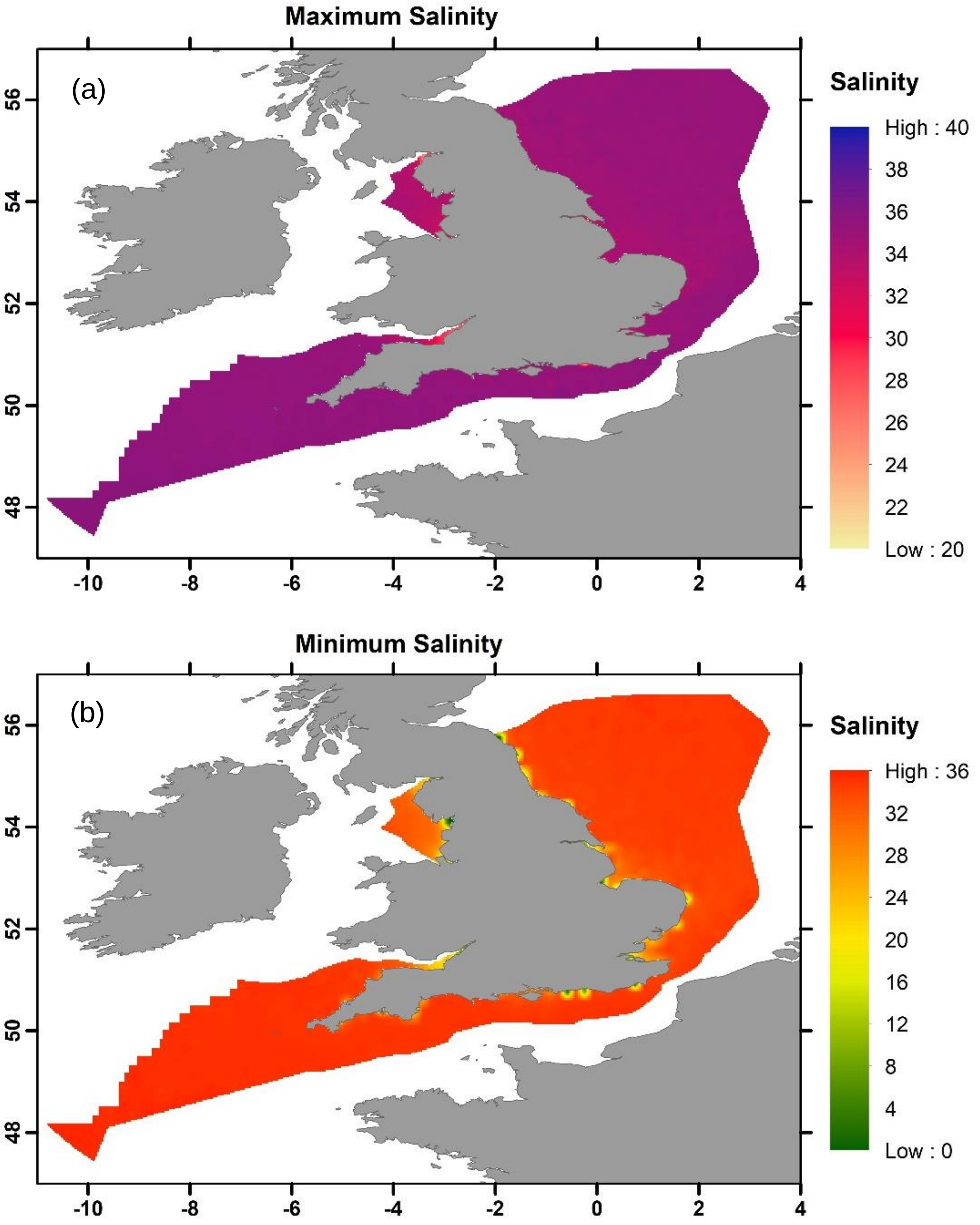


Figure 13: Mean dissolved oxygen level (a) and the 10% light penetration depth (b) in the English Economic Exclusion Zone. For details on construction of these layers see 2.3.3 & 2.3.4.

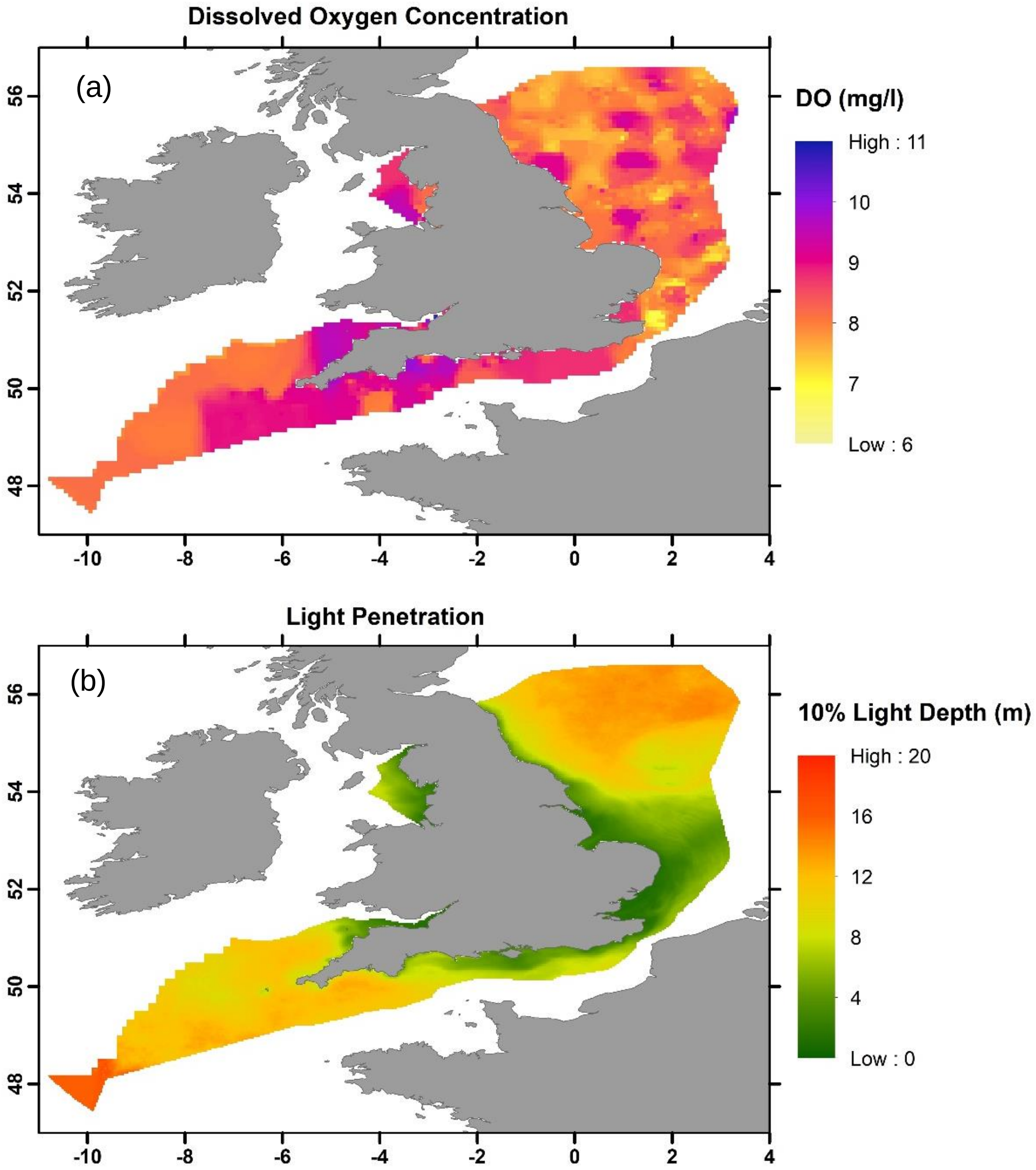
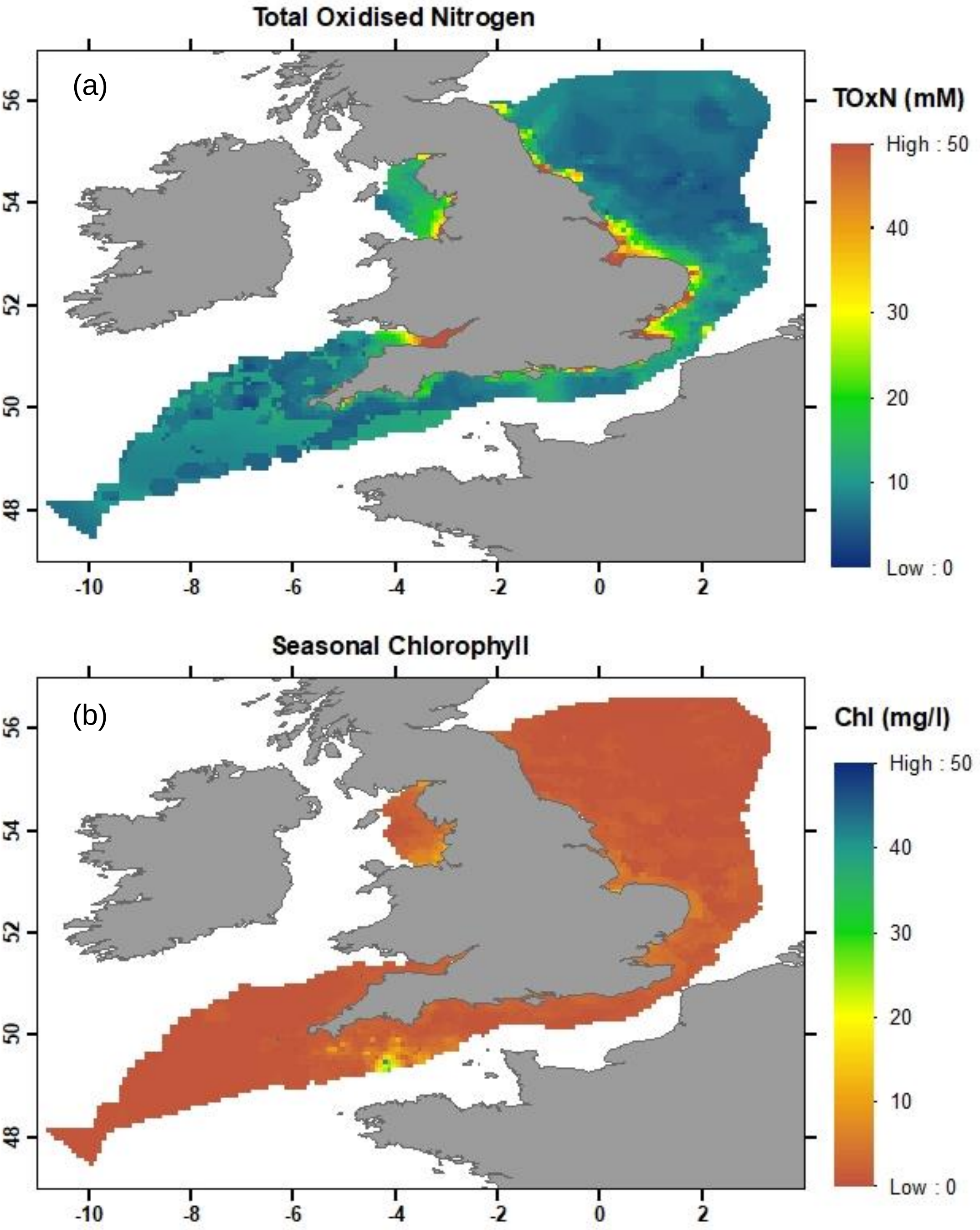


Figure 14: Total Oxidised Nitrogen concentration (a) and the seasonal chlorophyll concentration (b) in the English Economic Exclusion Zone. For details on construction of these layers see 2.3.5 & 2.3.6.



4.2 Classified environmental data

The environmental variables were classified in optimal, suboptimal and unsuitable ranges, according to the thresholds summarised in tables in Section 3. Resulting classified areas for the 14 species are shown in Annex 2.

In order to overlay environmental layers, they were resampled onto a common grid (1/12 degree resolution). The environmental data were then classified according to conditions suitable for aquaculture growth and farming as determined by a literature search (see Section 3.1). Each environmental variable was classified according to a 3-tier classification:

- unsuitable = conditions considered unsuitable for aquaculture growth or survival;
- suboptimal = aquaculture species can grow but potentially at reduced rates (e.g. lower yield);
- optimal = most suitable conditions for aquaculture of the species.

4.3 Generation of the suitability map

The environmental layers were combined into a suitability index following the method described in Capuzzo *et al.* (2014) and further developed in Capuzzo *et al.* (2018). In summary, in order to create an overall map of environmental conditions suitable for aquaculture and cultivation, the classified layers (optimal/suboptimal/unsuitable) were overlaid. Only grid cells where all variables were at least ‘suboptimal’ were considered in the suitability map. If any variables were considered ‘unsuitable’ then the corresponding grid cell was given a suitability of zero.

The suitability index is a count of the number of ‘optimal’ variables divided by the number of variables taken into account. The index ranges between 0 (no variables are in the optimal range) and 1 (all variables in optimal range). A maximum of 8 variables were used (see Section 3.1); if, for example, 6 variables were in an optimal range the suitability index score would be 6/8 = 0.75.

4.4 Seaweed aquaculture suitability maps

The classified data layers were combined into the suitability index as described above and are presented in Figure 15.

Saccharina latissima and *Laminaria digitata* had very similar growing conditions (compare thresholds in Table 2 with Table 3:), hence the resulting suitability index are almost identical and are discussed here together.

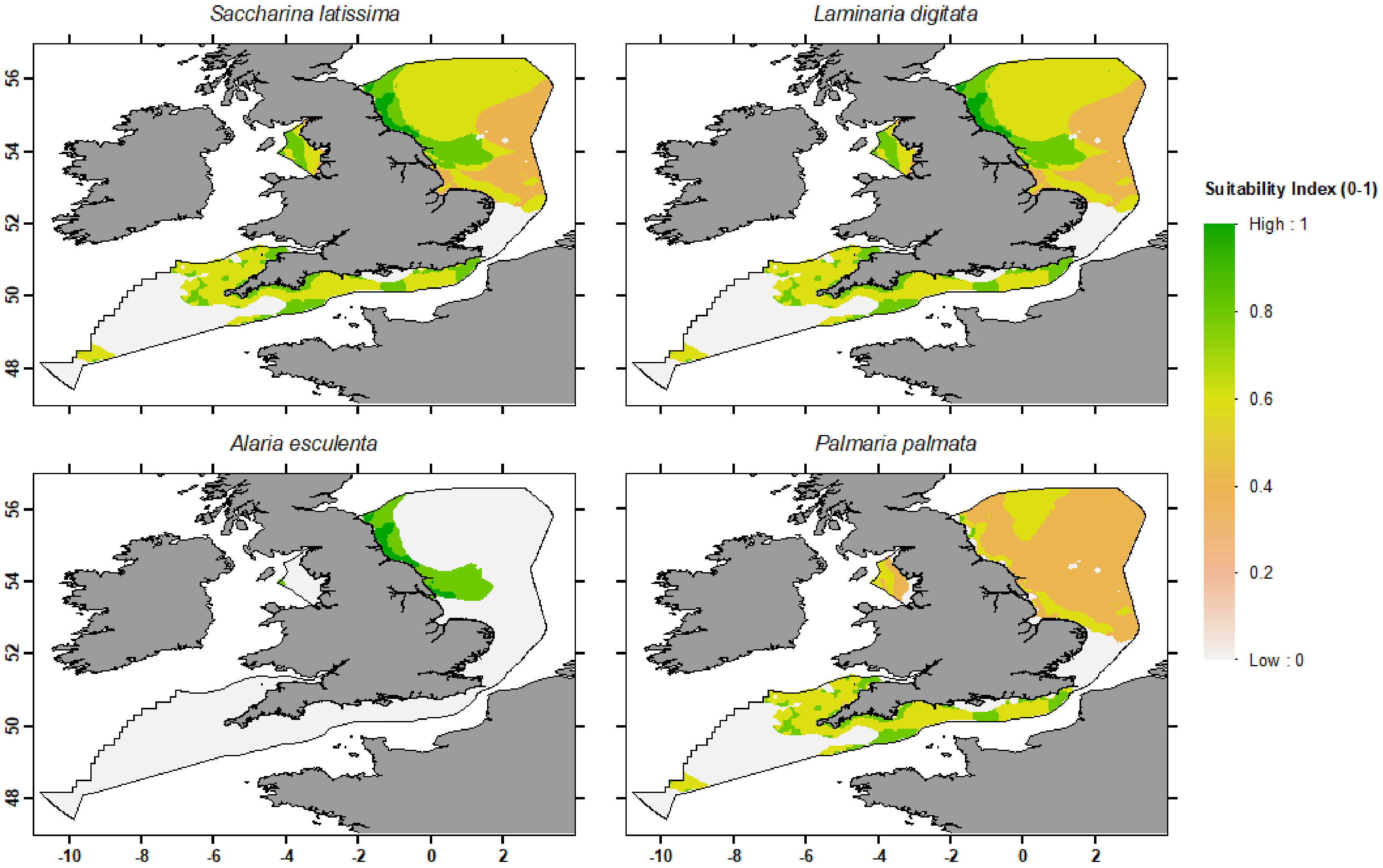
It appears that a good proportion of the English waters (58%, equivalent to approximately 29,000km^2) would present suitable (optimal or suboptimal) conditions for growth and farming of these two kelps. Particularly, the most suitable areas (highest number of environmental variables in optimal ranges, green colour) appear to be off the East Coast (from the Humber to the Scottish boarder, off Dover and

Folkestone, along the South West and offshore Liverpool Bay. Areas in the South of England had a lower suitability index score (suboptimal conditions) due to higher maximum temperature values (see Annex 2). The area between Lowestoft and Dover, the Bristol Channel and the area off the Isle of Wight (including the Solent) were classified as unsuitable due to the higher maximum temperature, exceeding the 18°C threshold (Table 2 and Table 3:).

Suitability of coastal areas for growth and farming of *Alaria esculenta* was driven by the maximum temperature of the 97.5 percentile, as this species of kelp requires temperature <16°C (Table 4:). Consequently, only a part of the East coast (from north of the Wash estuary to Northumberland), and small areas off north Norfolk, Start Point (in the South) and St. Bees Head (in the West) presented suitable conditions for *Alaria esculenta* growth and farming (Figure 15), equivalent to 9% of the total area considered (4,500km^2).

Dulse (*Palmaria palmata*) showed a wider suitable area for growth and farming compared to *Alaria esculenta* (Figure 15), due to its slightly higher tolerance to high temperatures (<18°C; Table 5). For sugar kelp, *Saccharina latissima*, coastal areas off Suffolk, Thames estuary, Isle of Wight, Liverpool Bay, Celtic Sea and Bristol Channel were considered unsuitable due to high maximum temperature. In addition, coastal areas adjacent to major river outflows (e.g. the Wash, Humber) were also considered unsuitable due to reduced salinity, as this species prefers marine salinity (>30; Table 5). The total coastal area considered suitable for growth and farming of this red seaweed was estimated to be 31.2% of the total area investigated (equivalent to 15,600km^2).

Figure 15: Suitable areas (optimal and suboptimal areas combined) for seaweed species growth off the English coast, obtained by intersecting the environmental variables shown in the appropriate section of Annex 2. For method see Section 4.3.



4.5 Finfish aquaculture suitability maps

The suitability maps for finfish aquaculture are shown in Figure 16 and they reveal that of the four considered species Atlantic salmon, rainbow trout and sea trout show potential throughout the Economic Exclusion Zone whereas Atlantic cod shows only limited potential.

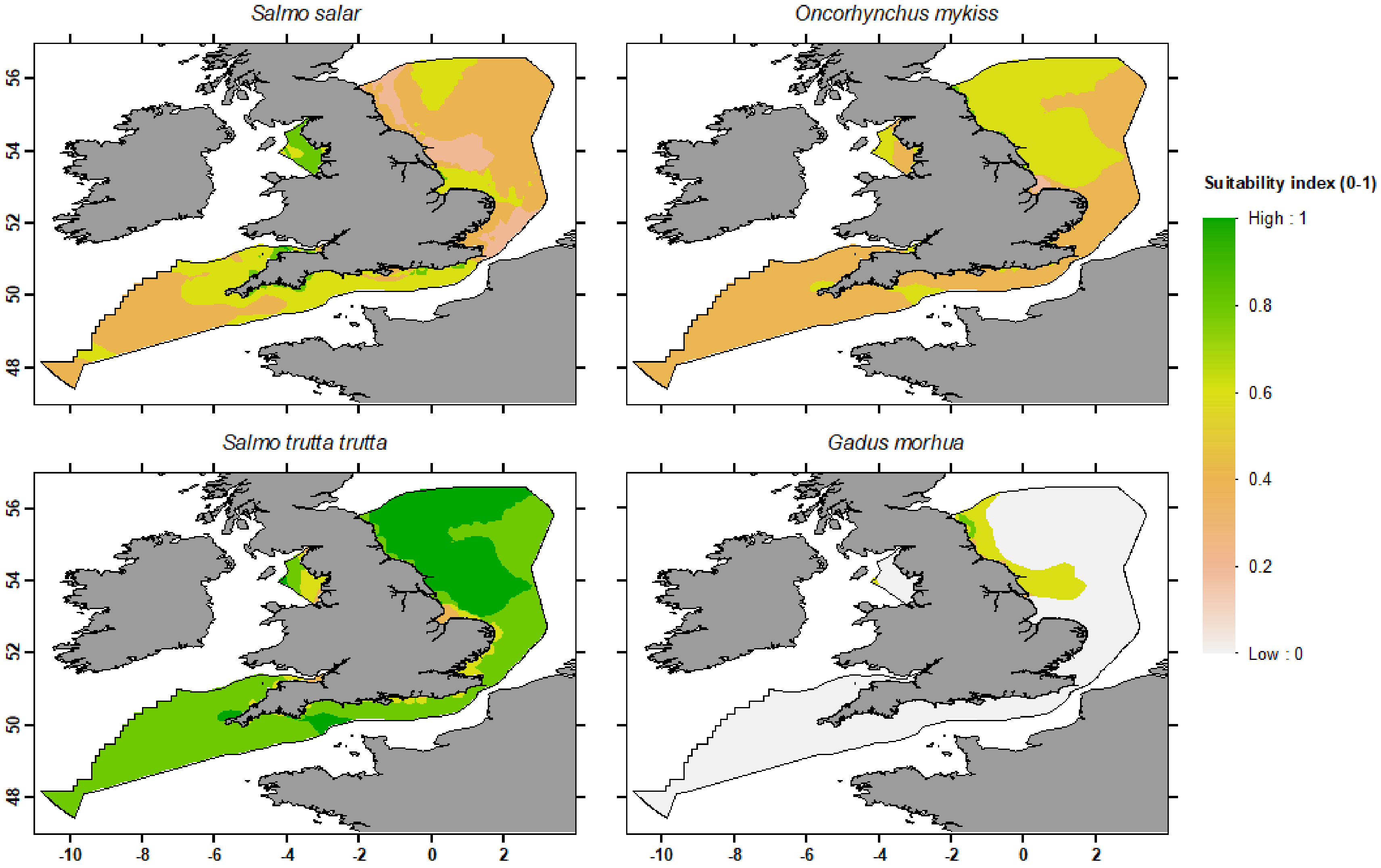
As may be expected the three salmonid species (Atlantic salmon, rainbow trout and sea trout) have similar suitability profiles as their common ancestry results in similar environmental threshold values. However, from these maps it appears that sea trout has the highest aquaculture potential with large parts of the map having a suitability score close to 1. The most promising area appears to be off the North East coast of England with some off-shore areas in North Cornwall and South Devon, especially for the southern region. The main reason for this difference is due to the salinity tolerance of sea trout.

For all the salmonids the maximum sea temperature across most of the map is suboptimal for their growth. For Atlantic salmon the minimum salinity reaches optimal levels off the coast of much of England but less so further out to sea. This is countered by a suboptimal sea temperature.

In contrast, for Atlantic cod 91% the defined sea area was unsuitable for aquaculture. This species shows optimal conditions across the map for salinity and dissolved oxygen and suboptimal conditions for the minimum temperature. Unsuitability what impacted by the maximum sea temperature in the south and west of the map. There is a small area off the North East coast that shows a suboptimal maximum temperature, and in the far north of this region and area showing optimal conditions. Further work should be considered to look at the bathymetry and temperature profile of the sea to understand if there are any options that involve submerging sea cages into areas with optimal maximum temperatures within the tolerance of this species.

For all finfish species the level of dissolved oxygen in the water is optimal for their survival and growth.

Figure 16: Suitable areas (optimal and suboptimal areas combined) for finfish species growth off the English coast, obtained by intersecting the environmental variables shown in the appropriate section of Annex 2. For method see Section 4.3.

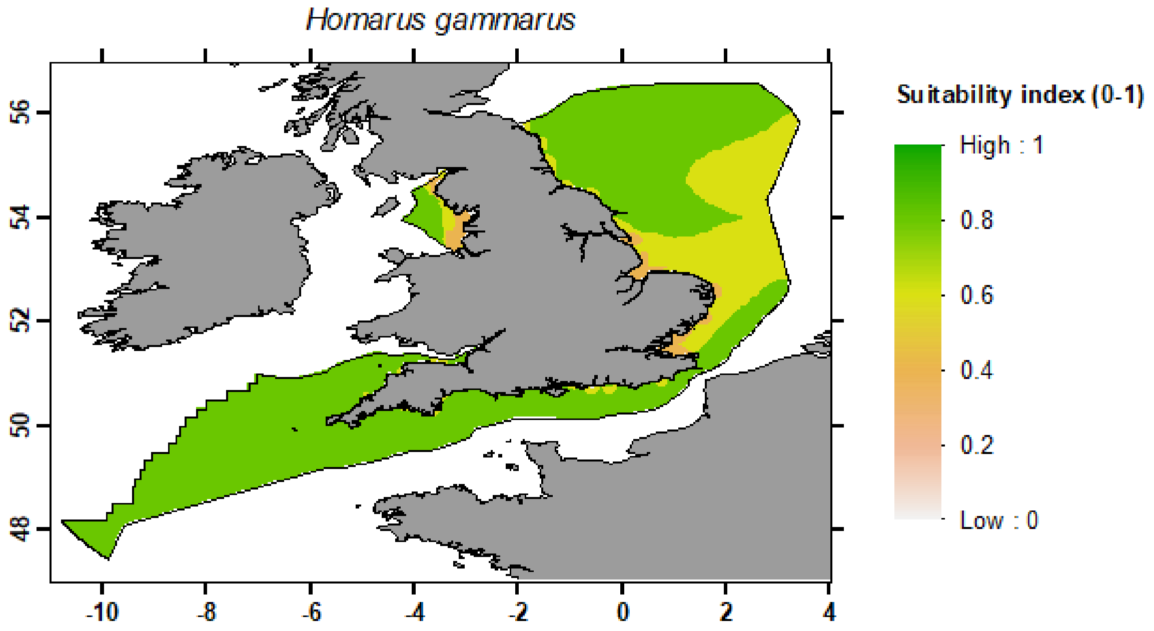


4.6 Crustacean aquaculture suitability maps

The suitability map for the European lobster shows a high degree of suitability across most of the map (see Figure 17). This is not too surprising as lobsters (and crabs) are caught from the wild in large sections of the mapped region.

Although there was aquaculture potential across all the Economic Exclusion Zone maps suggest that focus should be made to the English Channel, Celtic Sea and the area off the North East coast of England. The area off the west coast shows a high level of suitability but not in the close coastal areas. This difference is caused by a suboptimal minimum temperature in the region coupled with salinities outside of the optimal threshold levels.

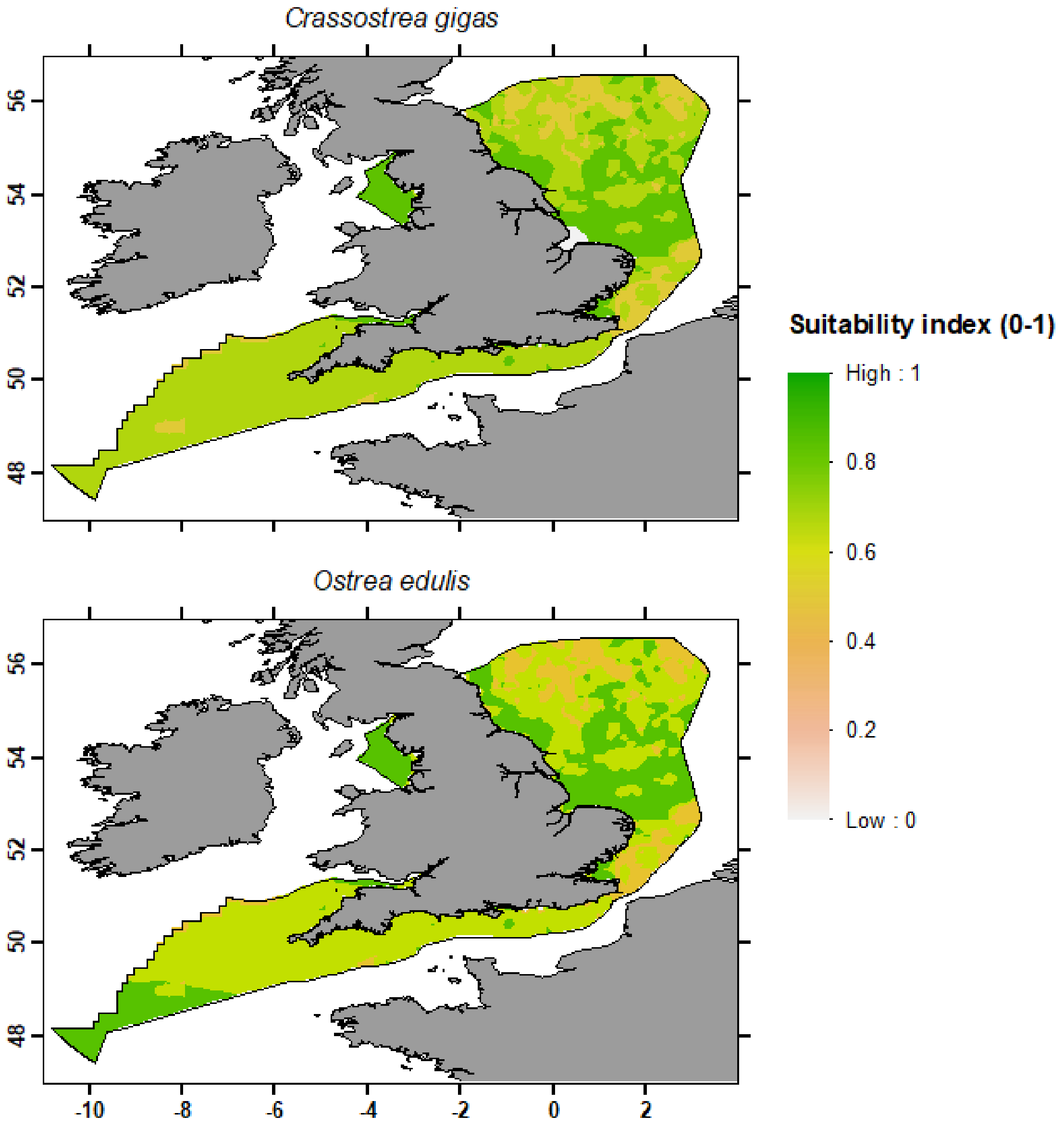
Figure 17: Suitable areas (optimal and suboptimal areas combined) for European lobster growth off the English coast, obtained by intersecting the environmental variables shown in the appropriate section of Annex 2. For method see Section 4.3.



4.7 Bivalve mollusc aquaculture suitability maps

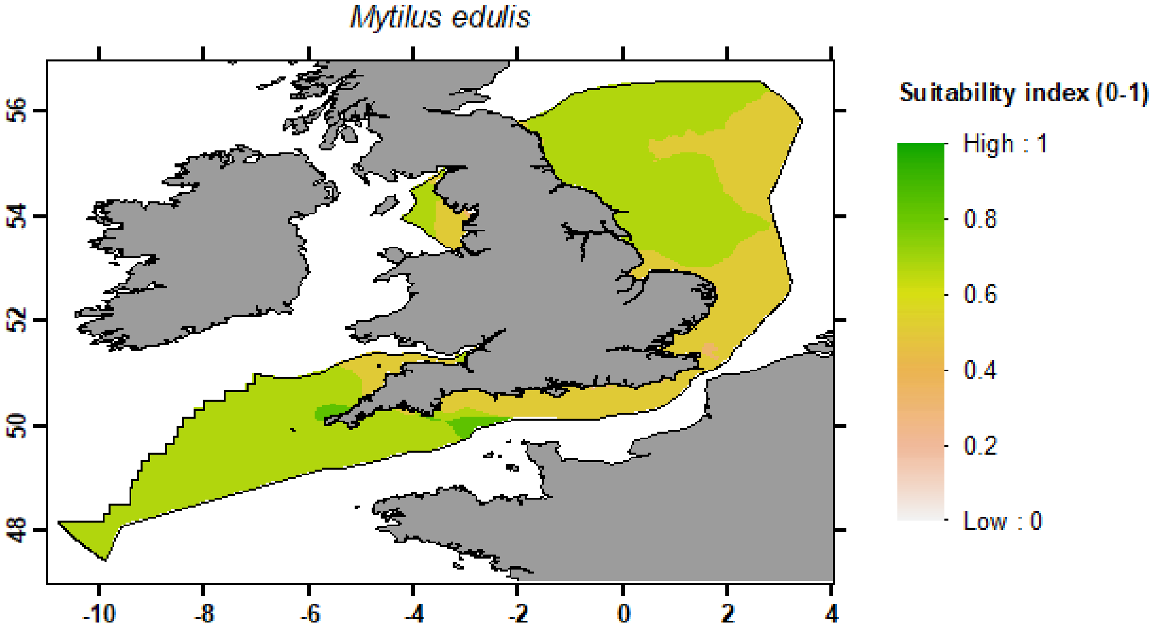
The bivalve mollusc aquaculture suitability maps suggest that the two species of oyster have the greatest potential across the English component of the UK EEZ (see Figure 18). The Pacific oyster has a suitability level above 0.5 across 98.5% of the English waters. The North West region and areas off the coast of Norfolk, Lincolnshire and Yorkshire show a very high potential. There are a number of smaller regions identified along the south coast such as regions around the Solent and West Sussex. A very similar pattern is observed with the native oyster due to very similar threshold levels for both species (compare Table 11 with Table 12).

Figure 18: Suitable areas (optimal and suboptimal areas combined) for oyster (Pacific and native) growth off the English coast, obtained by intersecting the environmental variables shown in the appropriate section of Annex 2. For method see Section 4.3.



The Blue mussel also shows a relatively good potential throughout English waters (Figure 19) but it is less pronounced that for the oyster species. Aquaculture potential is reduced due to suboptimal levels of the maximum salinity, minimum sea surface temperature (except for the south-west extent of the EEZ) and maximum sea surface temperature for regions south of Norfolk (above 30 for maximum salinity; below 8°C for minimum SST and above 12°C for maximum SST).

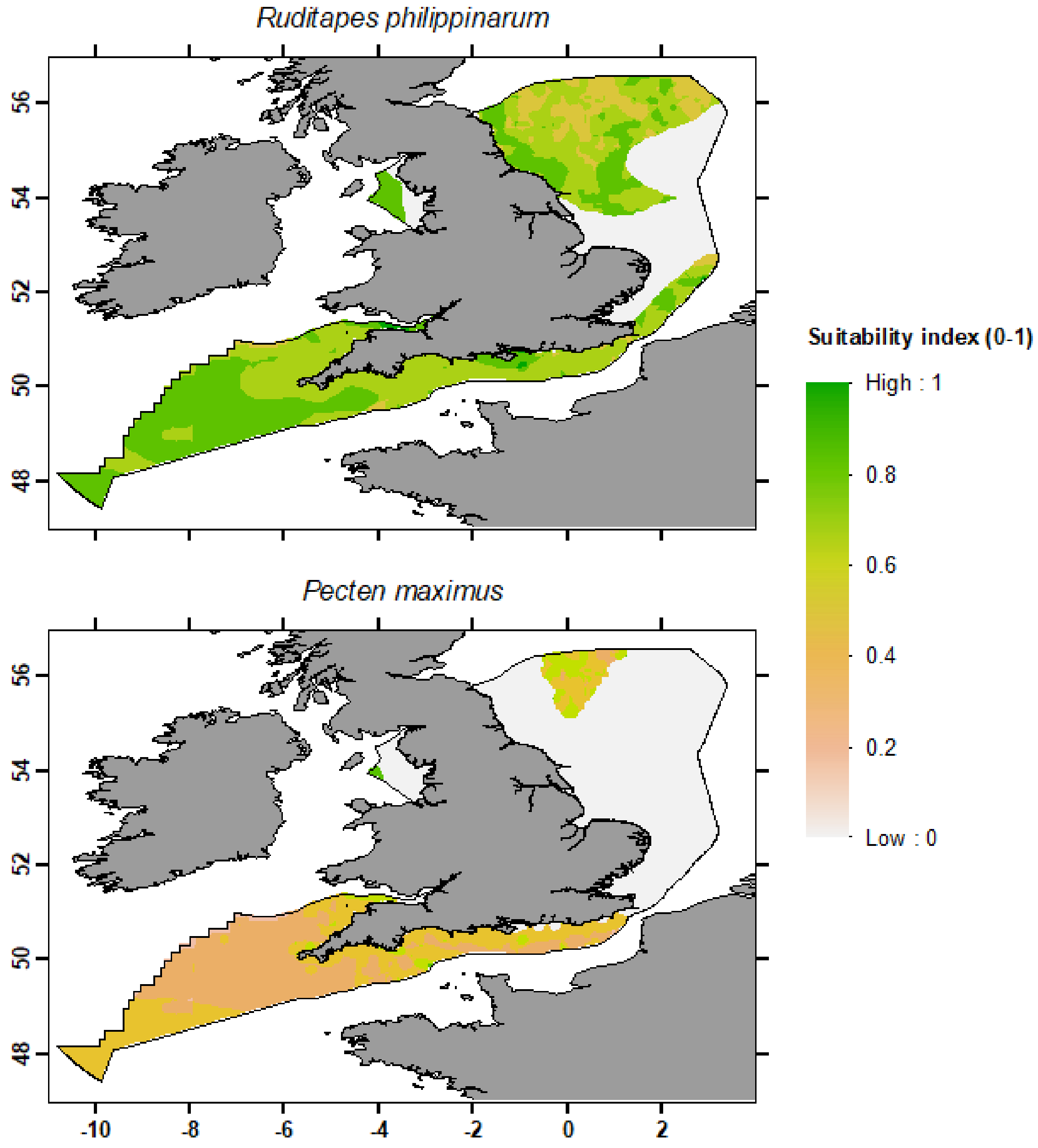
Figure 19: Suitable areas (optimal and suboptimal areas combined) for blue mussel growth off the English coast, obtained by intersecting the environmental variables shown in the appropriate section of Annex 2. For method see Section 4.3.



With regard to the Manila clam there are large areas that appear suitable for exploitation along the South Coast (English Channel and Celtic Sea) and off the coast of Yorkshire and Northumberland (see Figure 20). Cultivation appears to be unsuitable off parts of the East coast of England around Norfolk and Suffolk and off the North West coast. This is due to the minimum sea surface temperature in these regions being below that considered unsuitable for Manila clam culture.

For the five species of bivalve, the king scallop shows the largest area of English waters where aquaculture is deemed unsuitable. King scallop cultivation is unsuitable all along the East coast of England from Dover to Northumberland (see Figure 20). In addition, it is considered unsuitable along the North West coast of England. In both cases this is driven by a minimum temperature below that considered suitable for this species (minimum SST below 6°C). In comparison, aquaculture potential is strong along the English Channel and into the Celtic Sea.

Figure 20: Suitable areas (optimal and suboptimal areas combined) for Manila clam and King scallop growth off the English coast, obtained by intersecting the environmental variables shown in the appropriate section of Annex 2. For method see Section 4.3.



5 Technical constraints

5.1 Overview

This section of the report highlights the common aquaculture methods used for aquaculture and a methods technical requirements. Common aquaculture methods for each species considered here in Table 16. and in turn in this section (Aldon, 1998; Laing, 2002; Laing and Spencer, 2006; Cardia and Lovatelli, 2015; FOA, 2018a, 2018c, 2018d, 2018e, 2018f, 2018g, 2018i; Seafish, 2019b, 2019c, 2019d, 2019e, 2019f, 2019g).

Table 16: Common culture methods for aquaculture in the UK. Cages refers to flexible or rigid cage structures that are either floating or submersible.

	Aquaculture Methods							
Species	Bottom culture	Bottom-secured (trestle/poles)	Rope/textile (suspended)	Bags/lantern nets (suspended)	Sea Based Container Culture (suspended)	Cages	Raceways	Recirculating Aquaculture Systems
Seaweed								
Saccharina latissima		✓‡	✓					
Laminaria digitata		✓‡	✓					
Alaria esculenta		✓‡	✓					
Palmaria palmata		✓‡	✓					
Finfish								
Atlantic Salmon						✓	✓‡	✓‡
Rainbow trout						✓	✓‡	✓‡
Sea trout						✓	✓‡	✓‡
Atlantic cod						✓	✓‡	✓‡
Crustacean								
European Lobster	✓				✓			✓‡
Bivalves								
Pacific oyster	✓	✓						
Flat oyster	✓	✓						
Blue mussel	✓		✓	✓				
Manila clam	✓							
King scallop	✓	✓	✓	✓				

‡ - not covered in this report

Using these approaches the typical harvest times from juvenile to harvest size are indicated in Table 17. Harvest times are affected by the time of year of aquaculture deployment and the corresponding environmental factors during the production cycle.

Table 17: Typical harvest times for the aquaculture species considered in this report.

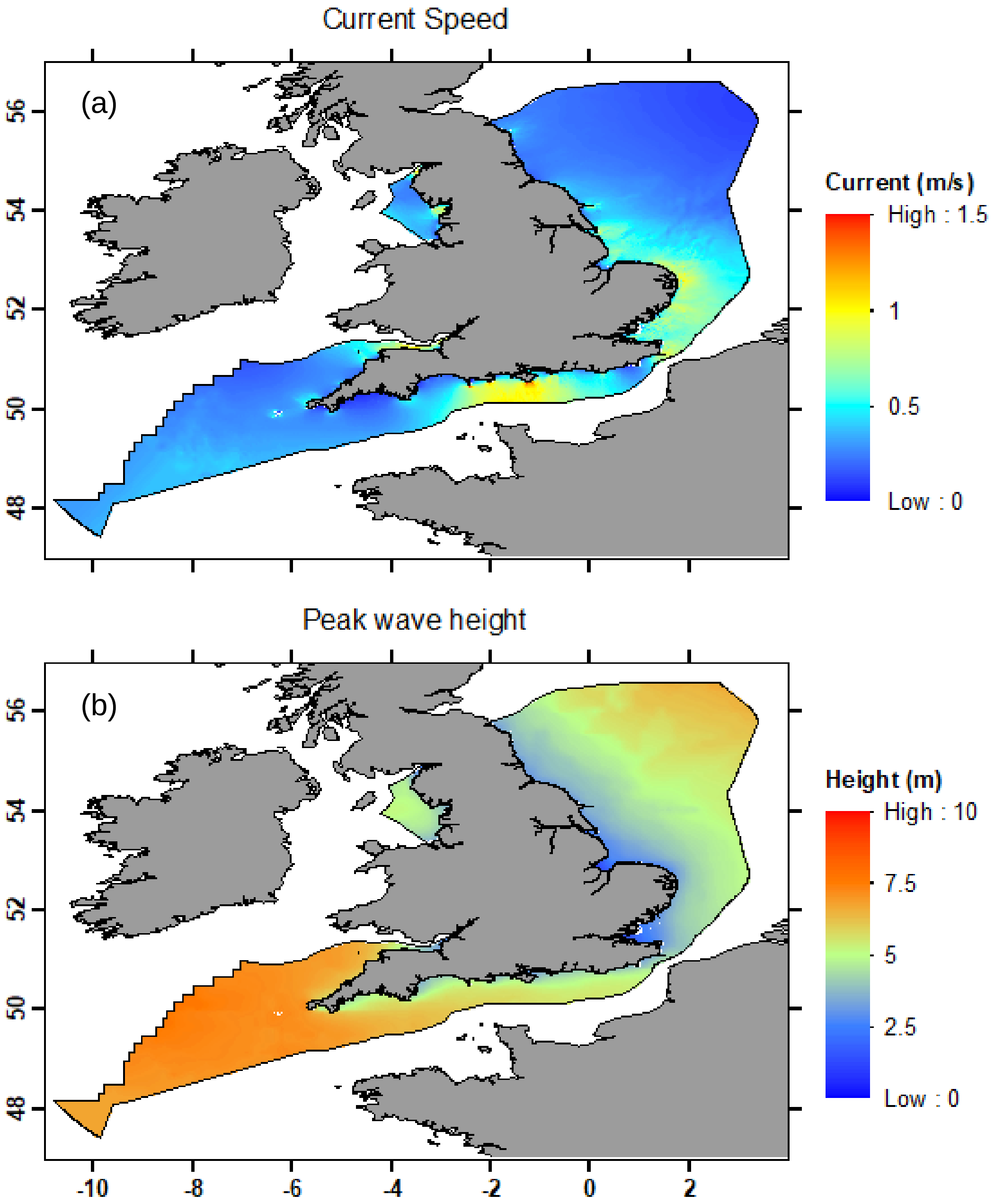
Category	Species	Typical Time to Harvest (yr)
Seaweed	*Saccharina latissima*	1-2
	Laminaria digitata	1-2
	Alaria esculenta	1-2
	Palmaria palmata	1-2
Finfish	Atlantic Salmon	1-2 (grow on in cages)
	Rainbow trout	1.5-2
	Sea trout	1-2
	Atlantic cod	2-3
Crustacean	European Lobster	5-7
Bivalves	Pacific oyster	2.5- 3
	Flat oyster	3-4
	Blue mussel	2-3 (rope); 1.5-3 (bottom)
	Manila clam	2-3
	King scallop	Southern England: 3-4 Northern England: 5-6

5.2 Summary of technical layers supplied

Annual average current was highest off the Isle of Wight (>1.25m/s), off East Anglia and Dover, and in the Bristol Channel, while the lowest average values were estimated between Start Point and Land’s End and offshore in the North Sea (Figure 21a).

In terms of peak wave height, a clear transition is noticeable, along the South coast, between the East and West of England, from the estuary of the Thames and Wash (with <2m peak wave height; Figure 21b), to the Celtic Sea with peak wave height of approximately 9m (Figure 21b). Generally, the East coast was characterised by peak wave height of <4m, with the exception of areas off Lowestoft and Felixstowe with slightly higher wave height than elsewhere in the region (Figure 21b).

Figure 21: Technical constraint layers for current speed (a) and peak wave height (b) experienced in the English Economic Exclusion Zone. Data supplied to the MMO to determine whether aquaculture methods are viable.

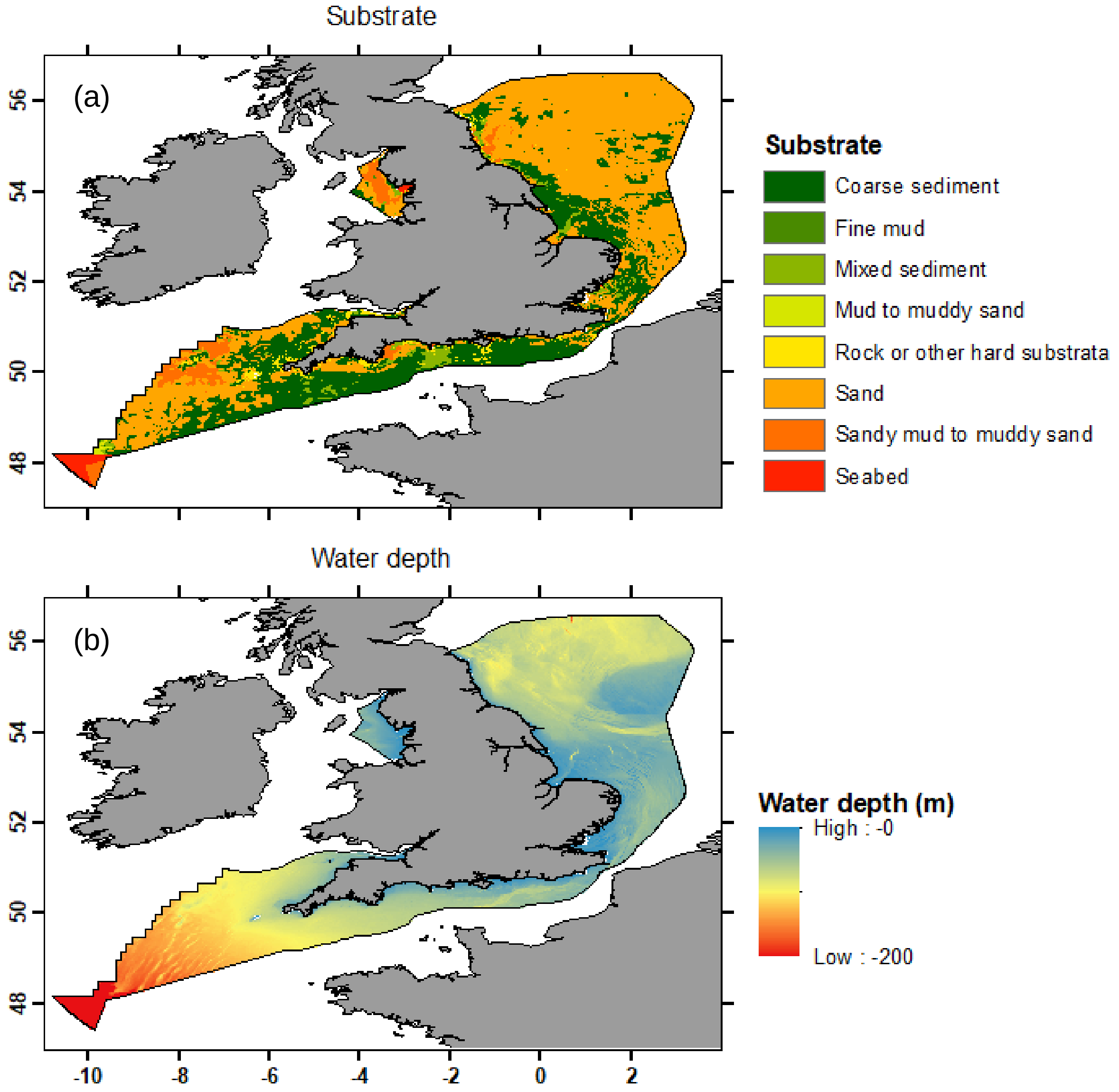


The seabed substrate layer was obtained from the EMODnet Seabed habitats data portal (http://www.emodnet.eu/seabed-habitats) and consisted of the “Substrate type” data layer from the EMODnet broad-scale seabed habitat map for Europe (EUSeaMap; scale of 1/250000). This data layer defines the substrate under the Folk 7 classification system. Substrate categories are fine mud, sandy mud, muddy sand, sand, coarse sediment, mixed sediment, rock and boulder and seabed (unclassified).

The seabed substrate in the English waters is mainly coarse sediment and sand Figure 22a). In the English Channel and Bristol Channel the seabed is mainly coarse sediment, with some sandy regions along the South Devon, Dorset and Sussex coast. There are also some localised rock and mixed sediment regions. The East coast is mainly coarse sediment on the coast but there is a large area of sand substrate off the north east coast. The coast of Yorkshire has an area of muddy sand which is also found off the north west coast (and in a small region off the South Devon coast).

Finally, bathymetry varied from shallow areas (<25m) from the Humber to the Isle of Wight, and the west of England, to the continental shelf edge in the Celtic Sea (>1000m; Figure 22b).

Figure 22: Technical constraint layers for substrate (a) and water depth (b) experienced in the English Economic Exclusion Zone. Data supplied to the MMO to determine whether aquaculture methods are viable. Water depths below 200m are coloured red.



5.3 Seaweed aquaculture

Seaweed are farmed suspended in the water column, either on ropes or on textiles, although the structure and shape of the farm can be variable (see Figure 23 and Figure 24 for some examples).

Figure 23: Overview of seaweed farming methods on lines in Europe from Buck and Grote (2018).

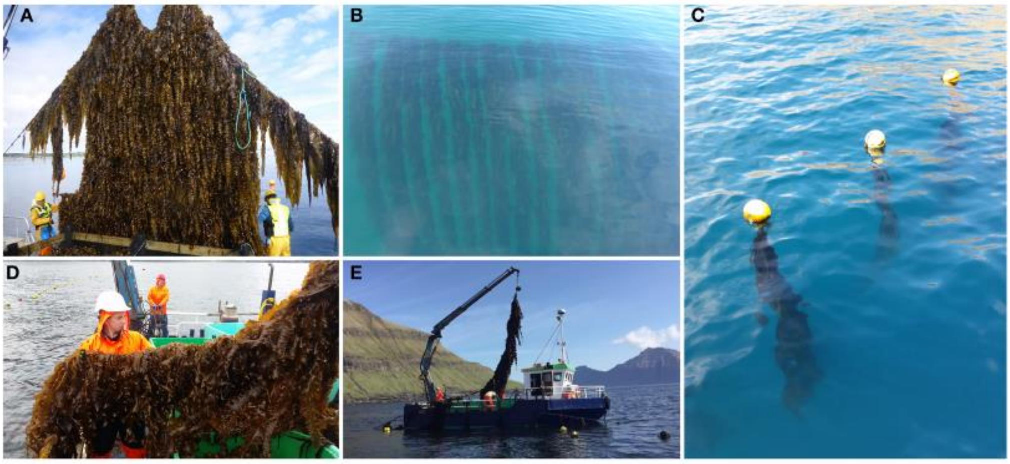
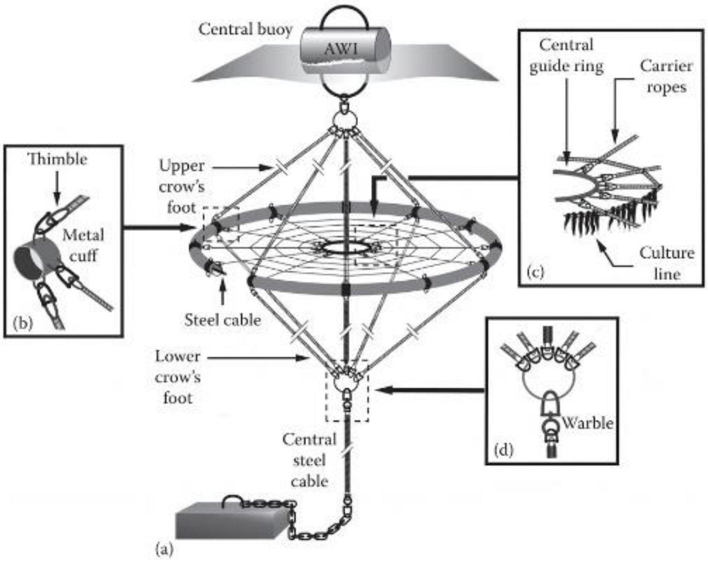


FIGURE 6 | (A–E) Offshore seaweed farms in Norway (Seaweed Carrier) and Faroe Islands (Macroalgal Cultivation Rig—MACR). **(A)** Harvest of seaweeds growing on the Carrier (upper left); **(B)** Underwater image of the kelps growing on the Carrier devices (upper centered); **(C)** Seaweeds hanging perpendicular from the backbone (upper right). **(D,E)** Harvest of *Saccharina latissima* on board of the vessel *Tongul* (lower left and centered) [Images **(A,B)** with permission of *SES*, Norway, and the publisher modified after (Buck et al., 2017b); **(C–E)** with permission of *Ocean Rainforest Sp/F*, Faroe Islands].

Figure 24: (a) Offshore ring device for the cultivation of seaweed, adopted to farm *Saccharina latissima* in the German Bight (b) *Saccharina latissima* cultivated on textiles (from Buck and Grote (2018) and https://www.innovationintextiles.com/sioen-founds-spinoff-company-to-sell-its-textile-based-seaweed-cultivation-substrates/ respectively).



(a)

(b)

Studies on recommended wave height or current speed for seaweed farming are very limited, as the tolerance of the farm to offshore conditions depends on the farm type and shape chosen (for example, whether a carrier devices or offshore ring device is employed).

Ranges of current speed and peak wave height were determined based on the study by Buck and Buchholz (2005) of *Saccharina latissima* aquaculture in the German Bight. The authors observed that the *S. latissima* plants at an offshore farm (Figure 24) withstood a maximum current velocity of 1.52m/s and wave height of 6.46m.

It is likely that farming at higher currents and wave height would be possible, however, there appears very limited evidence in literature. For example, the Ocean Rainforest farm, (http://oceanrainforest.com/) in the Faroe Islands, withstood a maximum significant wave height of 7-8m (Buck and Grote, 2018). Kelp plants in their natural environment can survive in very exposed environments, investing more energy into the development of the holdfast to avoid being dislodged. Therefore, the highest limit of thresholds adopted in this study for current speed and wave height were set considering the physical structure of the farm and its resistance in a high-energy environment.

In this study, peak wave height, for all seaweed species was considered optimal between 0-4 m, suboptimal between 4-6m, and unsuitable >6m (Buck and Buchholz, 2005); while current speed ranges for the 4 species are given in Table 18.

Table 18: Optimal, suboptimal and unsuitable ranges of current speed (m/s) for 4 seaweed species.

Seaweed species	Optimal	Sub-optimal	Not suitable	References
Saccharina latissima	0.1-1.0	<0.1 1-1.5	>1.5	Buck and Buchholz, (2005) This study
Laminaria digitata	0.25-1.0	<0.25, 1.0-1.5	>1.5	Kerrison *et al.*, (2015) This study
Alaria esculenta	0.5-1.5	<0.5	>1.5	Buck and Buchholz, (2005); Tyler-Walters, (2008) This study
Palmaria palmata	0.25-1.0	<0.25, 1.0-1.5	>1.5	Same as *L. digitata*

Alaria can live naturally in very exposed sites (Lüning, 1990; Tyler-Walters, 2008), therefore the unsuitable threshold was dictated by the farm capacity to withstand currents and waves. *Palmaria palmata* is an epiphyte of *Laminaria digitata*, therefore the same current thresholds were used.

The possibility of a catastrophic loss of the farm during storm events must also be factored into the site placement, so a detailed study of the local wave climate should be considered (Capuzzo *et al.*, 2014). In this context, the WaveNet network (https://www.cefas.co.uk/cefas-data-hub/wavenet/) provides continuous data of wave height (as well as water temperature) along the English coast.

Water circulation through the farm and orientation of the lines should also be considered, particularly in larger cultivation areas, to ensure that the water around the farmed seaweeds is replenished of nutrients, throughout the farm. A minimum water flow of 0.1m/s is recommended (Kerrison *et al.*, 2015).

Depth requirement for the farm is dependent on the technique adopted for cultivation of seaweeds (e.g. ropes, textiles), the structure of the farm, accessibility via boat etc. Current pilot farms in Scotland and Northern Ireland are installed in water depth between 2 to 25m: the farm in Strangford Lough, Northern Ireland (Queen's University), 2-13m; the site in Sound of Kerrera, Scotland (SAMS), between 5 and 25m, and the farm in Lynn of Lorne between 15 and 25m (van der Molen *et al.*, 2018). However, the Ocean Rainforest farm, in the Faroe Islands is set at a location with depth between 50 and 70 (Buck and Grote, 2018). In this study optimal depth was considered >4m (with no upper limit).

5.4 Finfish aquaculture

5.4.1 Sea cages

Hatcheries supplying eggs and smolts are based on shore. Growth typically occurs in sea cages which are open net cages which can be square, rectangular or circular. Circular pens are typically used normally 90-110m in diameter and 15-20m deep, with several cages employed at a site to create a cage farm (Scott and Muir, 2000; Kumar and Karnatak, 2014; Cardia and Lovatelli, 2015). Circular cages are advantageous as they have simplified mooring systems due to their lighter weight, have a beneficial cost/volume ratio and are more resistance to dynamic stresses experienced in exposed sites (Kumar and Karnatak, 2014). There are many different types of offshore cages structure including floating flexible, floating rigid, semi-submersible flexible, semi-submersible rigid and submersible rigid (Scott and Muir, 2000). The advantage of submersible or semi-submersible cages is that they can be positioned away from the high energy regimes of the surface water, so could potentially be cheaper and reduce damage to fish stocks. For the purposes of this report, technical constraints will be optimised for floating, circular cages as these are the most proven economically at present.

Choosing the correct site for the sea cages is important because it influences the mortality and growth conditions of the finfish and also affects running costs. Site selection is a compromise. A key factor to consider is the exposure of the site to wind and wave action. An offshore and exposed site requires higher specification equipment, and increased running costs but fish welfare is improved and environmental impact lessened. A sheltered and protected site will have less damaging waves and currents but is likely to have a greater environmental impact (Cardia and Lovatelli, 2015).

The optimal, suboptimal and unsuitable threshold levels for the technical constraints for finfish aquaculture in sea cages is shown in Table 19 with expanded detail in the accompanying sections.

Table 19: Technical constraints for aquaculture of finfish in sea cages.

Constraint	Optimal	Sub-optimal	Not suitable	References
Bathymetry (m)	25-50	10-25, >50	<10	Johansson *et al.*, 2006; Cardia and Lovatelli, 2015
Current Speed (m/s)	0.25-0.5	0.02-0.25, 0.50-0.75	<0.02, >0.75	Laing and Spencer, 2006
Wave Height (m)	<9		9	Falconer *et al.*, 2013
Substrate	Coarse sediment, Sand, Sandy mud, Muddy sand, Fine mud	Mixed Sediment, Rock and Hard, Seabed	None*	Falconer *et al.*, 2013; Cardia and Lovatelli, 2015

Bathymetry

In general, aquaculture using cages requires a water depth above that observed in coastal (within 500m of land) areas. Although there are a range of cage sizes available, for economic and fish health reasons it is advantageous to have a water depth in the cage of at least 9m (Johansson, 2006). Furthermore, to prevent the cage from dragging on the sea bed an additional 1m is required at the very minimum, which places a minimum depth requirement of 10m.

It is recommended to have at least 15m between the bottom of the cage and the sea bed to allow a wider dispersion of cage waste (Cardia and Lovatelli, 2015) and ideally the bottom of the cage should be no deeper than 50m as this will require specialist diving operations for cage maintenance and installation of the moorings. This suggests an optimum water depth range of 25m to 50m.

Current speed

The current speed is a critical technical factor because it accounts for approximately 70-75% of the total forces exerted on a typical mid-size cage farm (Cardia and Lovatelli, 2015). The current speed (and direction) can affect:

- water exchange so affecting dissolved oxygen concentrations
- cage movements and volumes
- diving operations
- solid and dissolved waste dispersal from the cage.

For salmon aquaculture, 0.25–0.50m/s is the optimal current speed and 0.75m/s is the maximum current speed recommended (Cardia and Lovatelli, 2015). Nath *et al.*, (2000) suggests an optimal current speed of 0.10-0.50m/s, a minimum current speed of 0.02m/s, and a maximum of 1m/s based on the biological needs of Atlantic salmon. Although a sea cage can be operational below 0.25m/s, these biological constraints will be added to ensure optimal siting.

Wave height

Wave action accounts for around 20-25% of the forces acting on a typical mid-sized cage farm (Cardia and Lovatelli, 2015). Wind generated waves are influenced by wind speed, the surface area of open water over which the wind blows, the time duration and the depth of the water. The effect of the wave action dissipates with increasing depth below the surface, with waves generally being more destructive closer to shore.

Falconer *et al.*, (2013) employed a range of significant wave heights when modelling potential aquaculture sites in the Western Isles off the North-West coast of Scotland. They used cage specific parameters based on the potential location of the cage (sheltered, semi-exposed, exposed and offshore). For this study the offshore wave height will be employed which is considerably higher than that for a sheltered site (1.5m; see Falconer *et al.*, 2013).

Substrate

The sea-bed characteristics are important in determining the possibility for anchor embedment for the cages (Cardia and Lovatelli, 2015). The sea-bed anchor can be a deadweight or drag-embedment anchor, the latter functioning well in thick mud, clay or sand or in a pebble substrate. A deadweight anchor can be used in rocky or stony substrates.

The presence of sensitive habitats on the seabed may also make an area unsuitable to anchorage or deployment of a cage farm and should be considered for any area of fish farm development as part of the planning constraints.

Other considerations

In addition to those environmental conditions above other parameters that could be considered are:

- **Sediment Load:** High levels of suspended sediment can affect feeding and may choke farmed salmon. This is not well documented for any of the species considered here but a maximum suspended sediment of 25mg/L is recommended for salmon culture and therefore a similar value is likely for the other species (Newcombe and Jensen, 1996)
- **Presence of contaminants in the water:** The presence of other contaminants in the water course will affect the siting of a cage. These contaminants may come from domestic effluent or from industrial discharges and can affect growth of the fish or make the meat unfit for consumption (Baluyut, 1989).

5.4.2 Raceway aquaculture

A raceway is an artificial channel used in aquaculture that is based on-shore and involves using a diverted water course to provide a continuous water flow to a series of ponds (Baluyut, 1989). Such systems have been used to culture juvenile salmon and rainbow trout but would be unlikely to be useful for Atlantic cod because the water source is usually freshwater. The on-shore nature of this method means that it will not be considered in this report.

5.4.3 Recirculating aquaculture systems

Recirculating Aquaculture Systems (RAS) are on-shore systems in which water is continually recirculated around containment tanks in which the fish are housed (Baluyut, 1989). RAS allow the quality of the water to be controlled and reduces the environmental impact of the farming process. The RAS approach can be used for freshwater and seawater species and would be suitable for all 4 species considered in this report although the on-shore nature of this method means that it will not be considered in this report.

5.5 Crustacean aquaculture

5.5.1 Recirculating aquaculture systems

Recirculating Aquaculture Systems (RAS) are on-shore systems in which water is continually recirculated around containment tanks in which the lobsters are housed. This approach is routinely used in the hatchery process and has been adopted for grow-on of juvenile lobsters (mainly for restocking of wild stocks; see Bignell *et al.*, 2016 and Seafish, 2019b). Due to economic constraints RAS has yet to be adopted as a main-stream method for large scale adult lobster production. This method will not be considered in this report.

5.5.2 Sea based container culture

European lobster has been successfully grown on using a variety of Sea based container culture systems (SBCC, see Bignell *et al*., 2016). The nature of the container will influence environmental factors such as the current speed required to produce a sufficient exchange of water in the SBCC. Bignell *et al*., (2016) suggest the use of a few larger containers, oyster baskets, for lobster growth, and highlighted the importance of water flow on dissolved oxygen availability, removal of harmful wastes and reduction of biofouling. The optimal, suboptimal and unsuitable threshold levels for the technical constraints for lobster aquaculture in sea-based container culture is shown in Table 20.

Table 20: Technical constraints for aquaculture of lobster in sea-based container culture.

Constraint	Optimal	Sub-optimal	Not suitable	References
Bathymetry (m)	5-50	50-60	<5, >60	This study
Current Speed (m/s)	0.05–0.25		>0.25 <0.05	Halswell *et al.*, 2018
Wave Height (m)	Engineering Solution to Limit impact of this factor			
Substrate	Rock and hard, Mixed sediment, Coarse sediment, Seabed	Sand, Sandy mud, Muddy sand, Fine mud	None*	This study

Bathymetry
The depth at which the SBCC are deployed does not appear to affect the growth of European lobster at sites in the sea around South West England (Ellis *et al.*, 2015; Halswell *et al.*, 2018). Although the SBCC can theoretically be used at any depth practical constraints occur in depths over 50m; such as installation and maintenance of mooring structures. In its natural habitat the European lobster is found in depths from 5m to 60m (FAO, 2018h). Therefore, it seems suitable to use 60m as the maximum depth.

Current speed
Good water flow and circulation is crucial for maintaining satisfactory dissolved oxygen concentrations and waste removal for lobster aquaculture. Halswell *et al.*, 2018 performed hydrodynamic assessment of SBCC systems to identify water currents which affect feeding and behaviour of lobsters in containment. Upper and lower velocity limits of 0.25m/s and 0.004m/s were established and that the design of the container affects the external velocity required to main suitable internal water flow. In this study oyster baskets were predicted to require an external flow of at least 0.05m/s and they performed well in the upper velocity experiments.

Wave height
Wave energy sources resulting in flow rates above 0.25m/s can inhibit the food gathering activity of lobsters and therefore their growth rate (Ellis *et al.*, 2015; Halswell *et al.*, 2018).

Substrate
The SBCC system is a suspended culture technique and therefore the type of substrate does not limit whether the method can be undertaken. However, obtaining mooring/anchoring for long-lines may be more difficult and costly in less firm substrates.

5.5.3 Bottom culture of lobster

Bottom culture of lobster tends to involve a restocking of wild populations from hatchery stock using a continual restocking and capture approach. Juvenile lobsters take about 4-7 years to reach the minimum landing size (Seafish, 2019b). The lobsters are caught using standard lobster pots. Optimal, suboptimal and unsuitable threshold levels for the technical constraints for lobster aquaculture on the seabed is shown in Table 21 with expanded detail in the accompanying sections.

Bathymetry
The European lobster natural habitat is offshore water and shallow sub-littoral regions from depths of 5 to 60m, although it has been found on the continent shelf down to depths of 150m (FAO, 2018h). Restocking bottom culture methods require existing populations to supplement and therefore the depth requirements will match the natural range.

Current speed and Wave height
These factors are not applicable for the nature of this culture approach.

Substrate
The juveniles seek shelter on the bottom and therefore sandy or muddy substrate is not preferred unless boulders or rocky outcrops are present, or the mud is compacted.

Table 21: Technical constraints for bottom culture of lobster.

Constraint	Optimal	Sub-optimal	Not suitable	References
Bathymetry (m)	5-50	50-60	<5, >60	This study
Current Speed (m/s)	0.05-0.25		>0.25 <0.05	Halswell *et al.*, 2018
Wave Height (m)	Not known			
Substrate	Rock and hard Coarse sediment, Mixed Sediment, Seabed	Sand, Sandy mud, Muddy sand, Fine mud	None	This study

5.6 Bivalve mollusc aquaculture

5.6.1 Bottom culture

Bottom culture involves a chosen nursery area that is sown with bivalve seed (or juveniles) and allowed to grow to harvestable size (Laing and Spencer, 2006). In the UK, the species *Mytilus edulis* (Seafish, 2019g), *Crassostrea gigas* (Seafish, 2019d), *Ostrea edulis* (Seafish, 2019c), *Ruditapes philippinarum* (Seafish, 2019a) and *Pecten maximus* (Seafish, 2019f) are typically cultivated using this approach (Dare, 1980; Roberts, 2018a, 2018b). Nursery sites are generally in relatively shallow water in accessible coastal regions in sub-tidal and intertidal zones or in estuarine areas. However, bottom culture can be undertaken in deeper waters using boats as dredges (Laing, 2002; Laing and Spencer, 2006). Maintenance of the stock is minimal and limited to occasional monitoring and predator removal. The ability to tolerate air exposure is species specific and an indication of the range of values tolerated by the species in this report are shown in the Table 22 below.

Table 22: Species specific tolerances to air exposure (Percentage of Time not submerged)

Species	Air Exposure Level			References
	Optimal	Sub-optimal	Not suitable	
Pacific oyster	0	0–34	>34	Laing and Spencer, 2006
Native oyster	0	0-34	>34	Laing and Spencer, 2006
Blue mussel	0	0–50	>50	Brenner *et al.*, 2012
Manila clam	0	0-50	>50	Laing and Spencer, 2006
King scallop	0	N/A	>0	Laing and Spencer, 2006

Table 23: Technical constraints for bottom culture of bivalves.

Constraint	Optimal	Sub-optimal	Not suitable	References
Bathymetry (m)	0-40	40-110	>110	Laing, 2002; Laing and Spencer, 2006; Bibby, 2015
Current Speed (m/s)	0.5-1.0	0.17-0.5, 1.0-1.5	>1.5	Laing and Spencer, 2006; Strand *et al.*, 2016; Franco, 2017
Wave Height (m)	Not specified – see below			
Substrate	Coarse sediment Sandy mud, Muddy sand, Fine mud, Mixed Sediment	Rock and Hard, Sand Seabed	None	This study

The optimal, suboptimal and unsuitable threshold levels for the technical for bivalve aquaculture on the seabed is shown in
Table 23 with expanded detail in the accompanying sections.

Bathymetry
Optimal bivalve growth occurs when fully submerged and some species, such as King scallop do not tolerate air exposure (see Table 22). The bathymetry data from EMODnet represents the mean depth from sea bed to sea surface and therefore a minimum depth would start at around the mid-point of the intertidal zone. The tidal range in the UK varies around the coast from about 0.5m to a maximum of 15m in the Bristol Channel (Woodworth *et al.*, 2009).

For bottom culture, the natural preferences of the species can be taken as a guide to the threshold for the environmental parameter. For depth these are shown in Table 24 below.

Table 24: Details of natural depth ranges of shellfish species.

Species	Natural depth range (m)	Reference
Pacific oyster	5-40	Hughes, 2008
Native oyster	<20 (15-30 best for culture)	Perry and Jackson, 2017
Mussel	<40	Perry and Jackson, 2017
Manila clam	1-10	Perry and Jackson, 2017
King scallop	10-110 (documented to 1846)	Hughes, 2008

Wave height
Wave exposure is an important factor to consider when siting a bottom culture in the intertidal and sub-tidal regions. Strong wave action can damage bivalves and cause detachment and can result in large losses during extreme conditions (Steenbergen *et al.*, 2005; OSPAR, 2010).

Mussel beds are found in a range of sites from extremely exposed to extremely sheltered areas. The effect of wave height, and therefore wave energy, on mussel attachment is dependent upon the density of the mussel bed and the substrate they are growing on (Price, 1982; Young, 1985).

There is little documented details on the optimum wave heights for bottom cultured aquaculture methods. For scallop, it is suggested that the optimum is a maximum wave height of 1m (Seafish, 2019f).

Current speed

Filter feeding bivalves can only feed and breathe when fully submerged and when a suitable water flow is present. The optimal current is considered to be around 1-2 knots (approximately 0.5 to 1m/s) but some species such as oyster can cope with weaker currents. For mussel, tidal flows of 17-35cm/s are suggested (FAO, 2018k; Seafish, 2019g) and these will be considered minimum currents.

Table 25: Natural tidal flow rates for bottom cultured bivalve species.

Species	Optimal	Sub-optimal	Not suitable	References
Pacific oyster	0.5-1.0	0.25-0.5	<0.25, >1.0	Seafish, 2019d
Native oyster	0.5-1.0	0.25-0.5*	<0.25, >1.0	Seafish, 2019c
Mussel	0.5-1.5	0.17-0.5, 1.5–3.1	<0.17, >3.1	Seafish, 2019g
Manila clam	0.5-1.0	0.25-0.5, >1.0	<0.25	Seafish, 2019a
King scallop	0.5-1.5	<0.5	>1.5	Seafish, 2019f

* - Tidal flows of less than 1 knot (0.5m/s) acceptable so using values for Pacific oyster.

Substrate requirements

For bottom culture the substrate requirements are very species specific and ideally reflects the natural habitat of the organism. In this study the preferred bottom-substrate (contained in the Seafish Cultivation Leaflets; (Seafish, 2019g, 2019f, 2019e, 2019d, 2019c, 2019b, 2019a)) were translated into the Folk 7 classification system (described in Section 5.2). Specifically, firm substrates or those requiring good anchorage were translated to “Rock and Hard”, “Coarse sediment”, “Mixed sediment” and “Seabed”. A high silt burden was expected from “Fine Mud”, “Sand”, “Muddy Sand” and “Sandy Mud” although in some cases the sand or mud may be compacted and therefore may provide anchorage.

Table 26: Natural substrate preferences for bivalves.

Species	Natural Range‡			References
	Optimal	Sub-optimal	Not suitable	
Pacific oyster	Rock and hard, Coarse sediment, Mixed sediment	Fine mud, Sand, Sandy mud, Muddy sand, Seabed*		This study

Species	Natural Range‡			References
	Optimal	Sub-optimal	Not suitable	
Native oyster	Rock and hard, Coarse sediment, Sand, Mixed Sediment, Sandy mud, Muddy sand	Seabed*		This study
Mussel	Rock and hard Mixed sediment Coarse sediment	Sand, Fine mud, Sandy mud, Muddy sand, Seabed*		This study
Manila clam	Mixed sediment Sand Sandy mud	Coarse sediment, Muddy sand	Rock and hard	Vincenzi *et al.*, 2006
King scallop	Coarse sediment, Sand, Mixed Sediment, Sandy mud, Muddy sand	Fine mud, Seabed*	Rock and hard	This study

‡ - The Substrate definitions are those from EMODnet (* Seabed refers to unclassified areas)

5.6.2 Bottom-anchored methods

These methods of bivalve culture require the culturing device to be directed fixed to the bottom. Examples of these approaches are trestle tables, poles and cage systems (scallops). Such techniques favour firmer substrates to provide better support for the aquaculture containers and so that they are less likely to result in high silt loads in the water. This means less maintenance is required to ensure clogging of mesh does not occur (Laing and Spencer, 2006).

Table 27: Technical constraints for bottom-anchored culture of bivalves.

Species	Optimal	Sub-optimal	Not suitable	References
Bathymetry (m)	0 – 3		>3	Laing and Spencer, 2006
Current Speed (m/s)	0.5–1.0	0.25-0.5	<0.25, >1	Seafish 2019a, 2019b, 2019c, 2019d, 2019e, 2019f, 2019g
Wave Height (m)	Information gap			
Substrate	Rock and hard, Coarse sediment, Mixed sediment	Sand, Sandy mud, Muddy sand	None	This study

The optimal, suboptimal and unsuitable threshold levels for the technical constraints for bivalve aquaculture using bottom-anchored methods is shown in Table 27 with expanded detail in the accompanying sections.

Bathymetry

The main constraint on the operational depth of these systems is the ability to access the culture for maintenance and monitoring. Trestle tables are typically employed in tidal areas where the table is submerged for part of the day (Laing and Spencer, 2006). Theoretically these could be deployed at greater depths but practically this is unlikely. For the purpose of this report a maximal depth of 3m is considered a suitable depth for trestle table or pole cultivation.

The use of cage systems for scallops has been used at greater depths but may require divers for deployment and maintenance. This method could be considered in the event of suitability for culture of scallops being indicated at depths greater than 3m.

Current speed

As filter feeders the velocity of the water in which the bivalves are cultured is an important factor. Ideally, the flow needs to be great enough to provide sufficient food and remove waste products generated. However, too high a flow rate will cause stress to the animal, reducing feeding, and also cause damage to the culture apparatus. The suggested current speeds are shown in Table 28.

Table 28: Suggested current speeds for the bottom-anchored culture of bivalve species.

Species	Natural Range (m/s)			References
	Optimal	Sub-optimal	Not suitable	
Pacific oyster	0.5-1.0	0.25-0.5	<0.25, >1.0	Seafish, 2019d
Native oyster	0.5-1.0	0.25-0.5	<0.25, >1.0	Seafish, 2019c
Mussel	Usually grown using suspended rope or bottom culture methods			
Manila clam	Not applicable			
King scallop	0.5-1.5	<0.5	>1.5	Seafish, 2019f

Wave height

The bottom-anchored methods for bivalve culture are situated in the near shore region and are therefore in tidal zones with shallow water. Site-selected suggests sheltered areas but there is little information on the effect of wave height on cultivation.

Substrate

The substrate requirements for this culture method is a combination of the ability to anchoring the culture apparatus and the natural requirements of the species (for example substrates producing high silt burdens are less favourable). The substrate constraints are shown below for trestles and trays.

Table 29: Substrate requirements for bottom-anchored culture methods for bivalves

Method	Substrate		Not suitable
	Optimal	Sub-optimal	
Trestle	Rock and hard Coarse sediment Mixed sediment	Sand Sandy mud Muddy sand	None
Trays	Rock and hard Coarse sediment Mixed sediment	Sand Sandy mud Muddy sand	None

5.6.3 Suspended culture techniques

The suspended culture techniques require the culturing device to be suspended in the water column. These may be suspended from buoys or long-line systems which are anchored to the surface either attached to a solid structure or by a drag-anchor. Examples include:

- rope cultures
- suspended oyster bags
- suspended lantern nets
- ear-hanging for scallops.

A large amount of mussel production is done using ropes that are dropped from buoys or long-line systems. The small mussel “spat” attaches to the rope via byssal threads and these strengthen as the mussel grows (Young, 1985). Because the mussel is very effective at attaching to a surface, and the number of threads increases with increased flow rates (Price, 1982) they can survive high flow rates. However, the strength of attachment can vary according to the environmental conditions present (higher average flow rates causes more byssal threads to be present (Price, 1982), the substrate, the size of the mussel, its location in the mussel bed and the orientation of the mussel to the water current (Dolmer and Svane, 1994).

Based on byssal growth the estimated potential strength of attachment is for water flows of around 2m/s (Mainwaring *et al.*, 2014). Although, mussels have been shown to withstand storm surges of up to 16m/s they are unlikely to adapt quickly and any sudden increase in flow increases the chance of dislodgement (Young, 1985). Furthermore, studies investigating off-shore rope culture of mussel in the German Bight illustrated mussel attachment over regular diurnal flow rates from 0 to 1.52m/s and mean significant wave heights of 1.49m, and maximum wave heights of 6.4m (Buck, 2007). Therefore, a more conservative maximum flow rate is suggested in this report.

The optimal, suboptimal and unsuitable threshold levels for the technical constraints for bivalve aquaculture using suspended culture methods is shown in with expanded detail in the accompanying sections.

Table 30: Technical constraints for suspended culture of bivalves.

Species	Natural Range (m/s)			References
	Optimal	Sub-optimal	Not suitable	
Bathymetry (m)	5–20	20-50	<5, >50	Laing and Spencer, 2005
Current Speed (m/s)	0.5–1.0	0-0.5	>1	Seafish 2019a, 2019c, 2019d, 2019e, 2019f
Wave Height (m)	Engineering Solution able to Reduce Impact for Suspension Cultures			Information Gap
Substrate	Any[1]			This study

[1] – substrate will have an impact on the ability/cost of mooring the rope/line.

Bathymetry

A minimum depth of water is required to ensure that the culture is sufficiently submerged in the sea water. Furthermore, the submerged system operates best if it is submerged in the water column and therefore a minimum depth of 5m is recommended (the off-shore cultivation of rope mussels 17 nautical miles into the German Bight used 5m submerged lines (Buck, 2007). However, some studies recommended siting above this 5m level (Filgueira *et al.*, 2018). The rope can be of varying length and could potential be used to reposition the cultures daily or seasonally as required.

The maximum depth is largely affected by the ability to deploy the aquaculture system and to maintain it. With specialist divers needed below 50m this has been considered as the maximum depth. However, with aquaculture apparatus development this may be possible down to 100m or more (Buck and Langan, 2017).

Current speed

As filter feeders the bivalves require a suitable flow of water across or through the suspended culture apparatus to ensure delivery of food and removal of waste. Flows of around 1 knot are preferential to ensure that waste material is removed and therefore the likelihood of fouling is decreased (Aldon, 1998; Laing and Spencer, 2006; Seafish, 2019e). Rope cultivated mussels can withstand quite large flow rates (Hunt and Scheibling, 2001). Scallops prefer moderate flow rates (0.2-0.9m/s) when grown in suspension cultures but can tolerate flows up to 1m/s (Seafish, 2019f) Table 31.

Table 31: Current speeds tolerated by bivalve suspended cultivation techniques.

Species	Natural Range (m/s)			References
	Optimal	Suboptimal	Unsuitable	
Pacific oyster	Usually grown in bags on trestle tables or using bottom culture methods			
Native oyster				
Mussel	0.5-1.5	< 0.5, 1.5-3.1	>3.1	Seafish, 2019e
Manila clam	Usually grown using bottom culture methods			
King scallop	0.2-0.9			Seafish, 2019f

Wave height

For suspended culture techniques the effect of wave height is largely negated by ensuring that the culture apparatus is submerged within the water column. The effect of wave height dissipates with increasing depth and therefore siting the culture at least 5m above the sea surface prevents wave height becoming a limiting factor. Further, the design of the suspension culture method can be used to reduce the impact of wave action on the cultures (for example see Freites *et al.*, 1999).

There appears to be limited studies in the literature exploring the effect of wave height on the growth and survival of bivalve suspension cultures. In a study by Freites *et al.* (1999) the growth of scallops in suspension (via oyster nets) was subjected to different levels of wave action by varying the position of the suspension buoy. In this study a greater than 25% change in growth rate was observed for the burrowing, sandy bottom dwelling scallop *Euvola ziczac* when exposed to wave action, with an increased wave action causing a decrease in mass of the scallop (Freites *et al.*, 1999). These experiments were performed in 8m deep waters and data for deeper water was not obtained in this report. A study on open ocean sea scallop culture in Canada (Davidson *et al.*, 2015) suggests a lower survival rate in suspension cultures that employ a flexible gear that is affected by wave action versus gear that is not. This represents a gap in the knowledge literature.

A study on Eastern oysters (*Crassostrea virginica*) has demonstrated the importance of culture gear on growth performance (Mallet *et al.*, 2013). One particular aspect of this is the influence of wave action on the culture conditions of the oysters, with the floating bag cultures performing considerably less well than more rigid gear.

For the purpose of this report it is assumed that engineering solutions are suitable to ensure that the effect of wave height on growth is limited.

Substrate

For these “off-bottom” culture techniques the type of substrate does not limit whether the method can be undertaken. However, obtaining mooring/anchoring for long-lines may be more difficult and costly in less firm substrates.

Table 32: Substrate requirements for suspended culture methods for bivalves.

Method	Substrate	
	Optimal	Suboptimal
Suspended Culture	• Rock and hard • Coarse sediment • Mixed sediment	• Sand • Sandy mud • Muddy sand • Fine mud • Seabed

6 Discussion

This study showed that waters off England present suitable areas for growth and farming of the 14 species investigated (including seaweed, finfish, crustacean and bivalve mollusc). Particularly, the kelps *S. latissima* and *L. digitata*, sea trout, lobster, oysters (*Crassostrea gigas* and *Ostrea edulis*) and blue mussel appeared the most suitable species for aquaculture, based on their environmental ranges for optimal/suboptimal growth. Rainbow trout and Atlantic salmon showed suitability across most of the English waters of the UK EEZ but were best suited to more Northerly regions. This was especially so for Atlantic salmon which showed a high level of suitability off the north west coast of England. Manila clam showed a mixed picture, with reasonably high levels of suitability in the English Channel and Celtic Sea and some coastal areas of the north east. However, large areas off the north west and east coast of England were deemed unsuitable for aquaculture due to the minimum sea surface temperature being lower than that suitable for the clam.

In contrast, farming of *Alaria esculenta* and Atlantic cod appeared to be limited by some environmental factors (e.g. too high sea surface temperature occurring in summer in parts of the English waters). Cultivation of King scallop was limited to the South and South West regions because the minimum temperature for this species is below that experienced elsewhere in English waters.

Temperature was the main driver dictating the suitability of a coastal area for growth and farming of seaweed and the bivalve molluscs Manila clam and King scallop. The coastal area off Suffolk, the Thames estuary, Bristol Channel, the area off the Isle of Wight and the Celtic Sea were particularly affected by temperature limitation. However, for seaweed cultivation, it is partially possible to mitigate for the high temperature restrictions, for example by using temperature tolerant strains of seaweed, moving the seaweed vertically into the deeper, cooler part of the water column during summer, or by harvesting the crop before the highest temperatures are reached. Clams and scallops can bury themselves to overcome cold periods, however this does limit their growth rate.

Validation of the suitability maps by comparing potential sites with naturally occurring populations (*in situ* observations) has not been considered in this report. In Capuzzo *et al.*, (2018) suitability maps for seaweed aquaculture were compared with *in situ* observations. This showed the limitation of this approach because aquaculture provided many of the necessary conditions not found in the wild (for example, a suitable substratum in a location that the seaweed could not otherwise attach). Aquaculture typically involves the uppermost water layer and therefore comparison between motile finfish and filter-feeding benthic organisms in their native habitats with those in aquaculture is also likely to be of limited value.

This report is complemented with a set of GIS layers representing the aquaculture suitability maps and the technical constraints imposed by the aquacultures systems used. It is envisaged that these outputs will be combined with other information by the MMO, such as on uses of the coast, traffic, distance to ports, etc., to identify the most suitable locations for farming (i.e. optimizing the farm yield, while reducing potential conflicts with other uses or activities of the coast). It is advised that sites of interest should be investigated at higher detail and resolution than carried out in this study (which intended to provide a wider view of suitability for the English waters).

Furthermore, it would be also important to consider proximity to potential sources of contamination (e.g. discharges from industry or treatment plants). This is important for the bivalve filter feeders as they can accumulate heavy metals and viruses which can be a problem with human health if they are consumed.

Finally, this study highlighted some gaps in data availability, on seaweed physiology and optimal growing ranges, on the technical constraints for the 14 species investigated, and of environmental data (for example, lack of measurements in offshore areas). It was particularly challenging to identify environmental thresholds for *A. esculenta* and *P. palmata*, therefore further research on the best growing conditions for these two species, would be encouraged.

7 Recommendations

The purpose of this study was to identify areas of potential interest for aquaculture inside the Economic Exclusion Zone of England. A key recommendation is that any identified suitable regions in this study are followed up with individual localised investigations. Such studies would use data layers with an increased resolution to enable more precise siting of aquaculture. Furthermore, for bivalve molluscs the effect of localised Suspended Particulate Matter (SPM) should be assessed. This should consider the site-specific nature of the seabed substrate, the depth of water and the contribution of organic and inorganic particulate matter to the total SPM. The ratio of inorganic SPM to organic SPM can affect the feeding behaviour of bivalves and the organic fraction may be from phytoplankton and/or detritus sources which can additionally impact feeding.

A second recommendation is that the data layers used in this report should be kept up to date as additional data becomes available. In particular, the incorporation of more *in situ* data is encouraged along with the augmentation of satellite and modelled data. This is recommended for both the environmental and technical data layers used in this study.

Through this study there appears to be a gap in understanding of the effect of wave height and water current on aquaculture systems. It is recommended that this knowledge gap is addressed. This could be achieved by developing hydrodynamic models to understand the impact of wave height and hydrodynamic on specific aquaculture systems. Such models could be validated using laboratory or in situ experiments.

As the aquaculture industry moves towards Integrated Multi-trophic Aquaculture (IMTA) it is recommended that the current study is progressed to highlight the possibility of this method in the Economic Exclusion Zone. Such an approach would require consideration of combinations of the species-specific suitability layers with the appropriate technical constraints.

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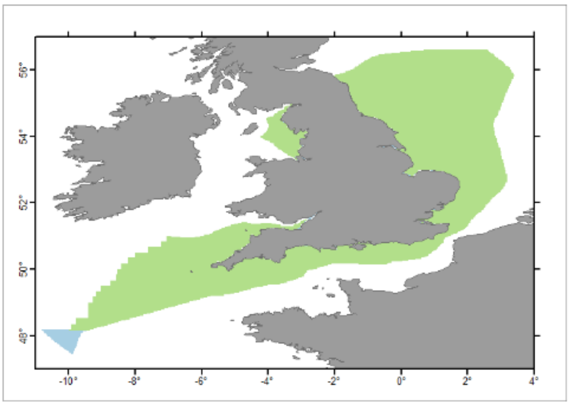
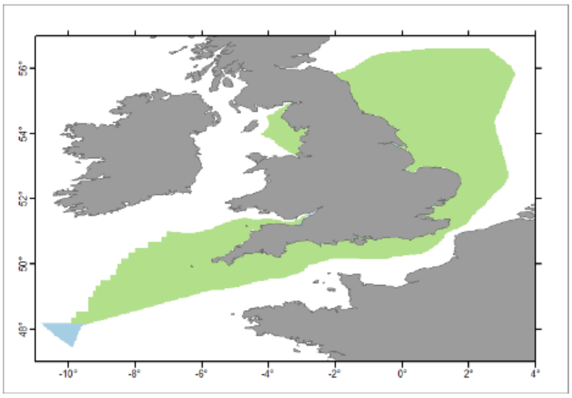
Annex A1. Data Provenance: Environmental Layers

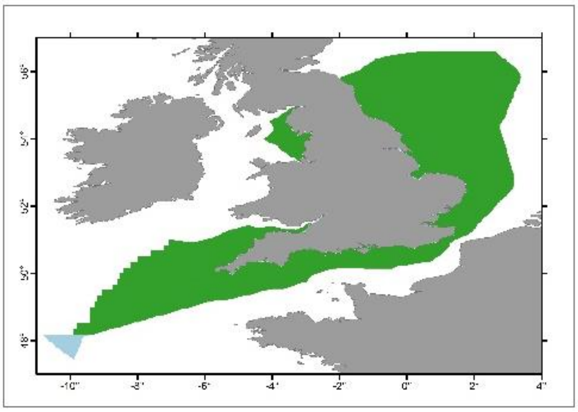
These GIS layers show the provenance of the data that has been used to generate the layer. For these layers **in situ** data is shown in green, **satellite** data in light green, **model** data in blue and **interpolated** data in light blue.



Maximum Temperature



Maximum Salinity



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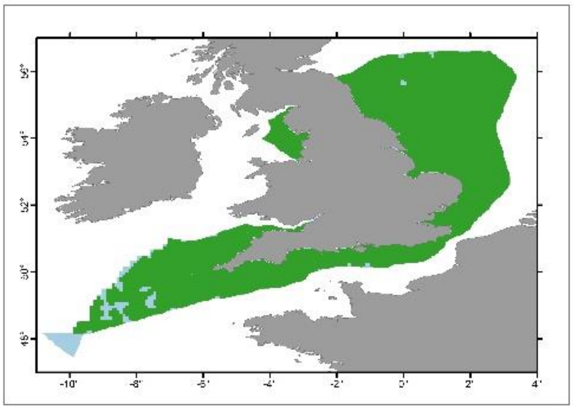

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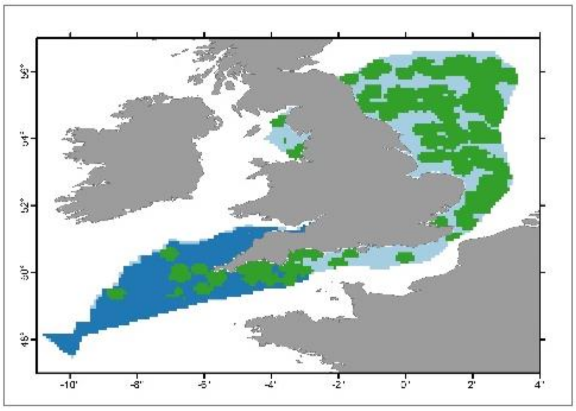
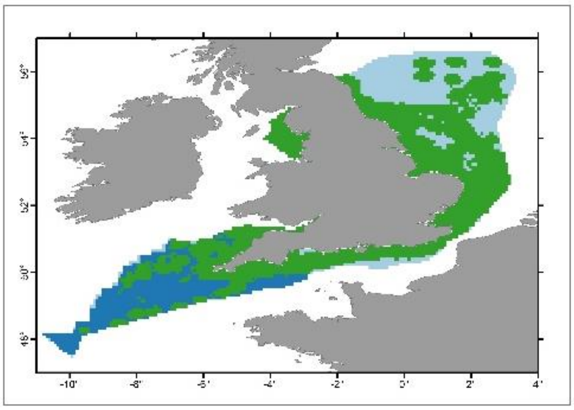
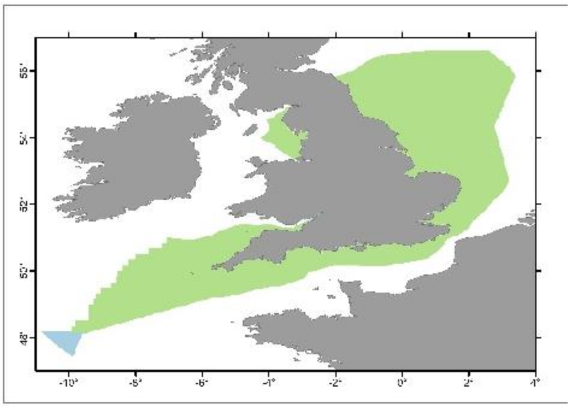
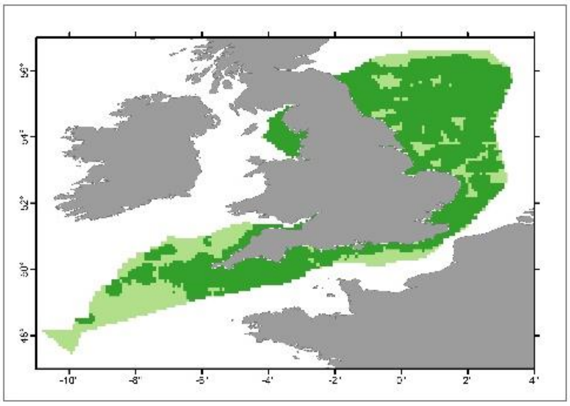
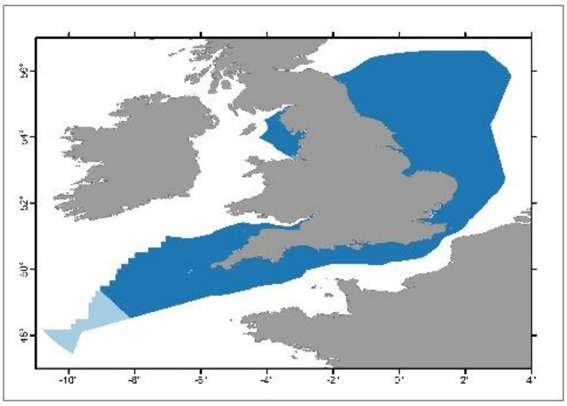
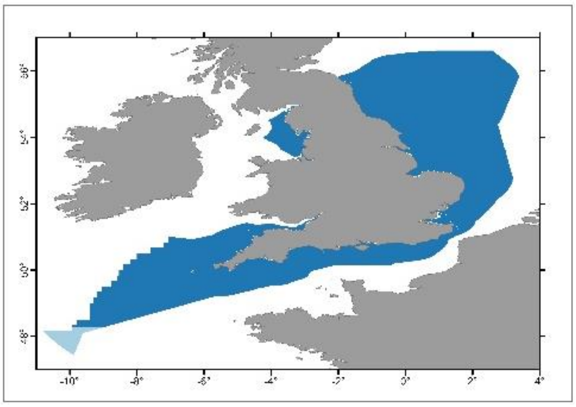
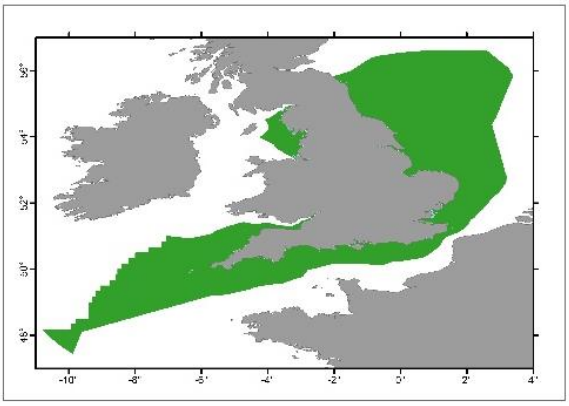
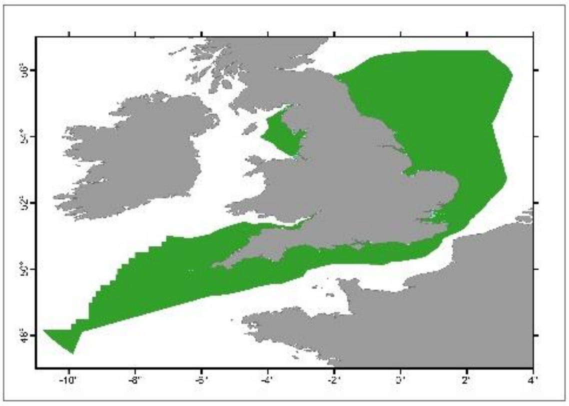


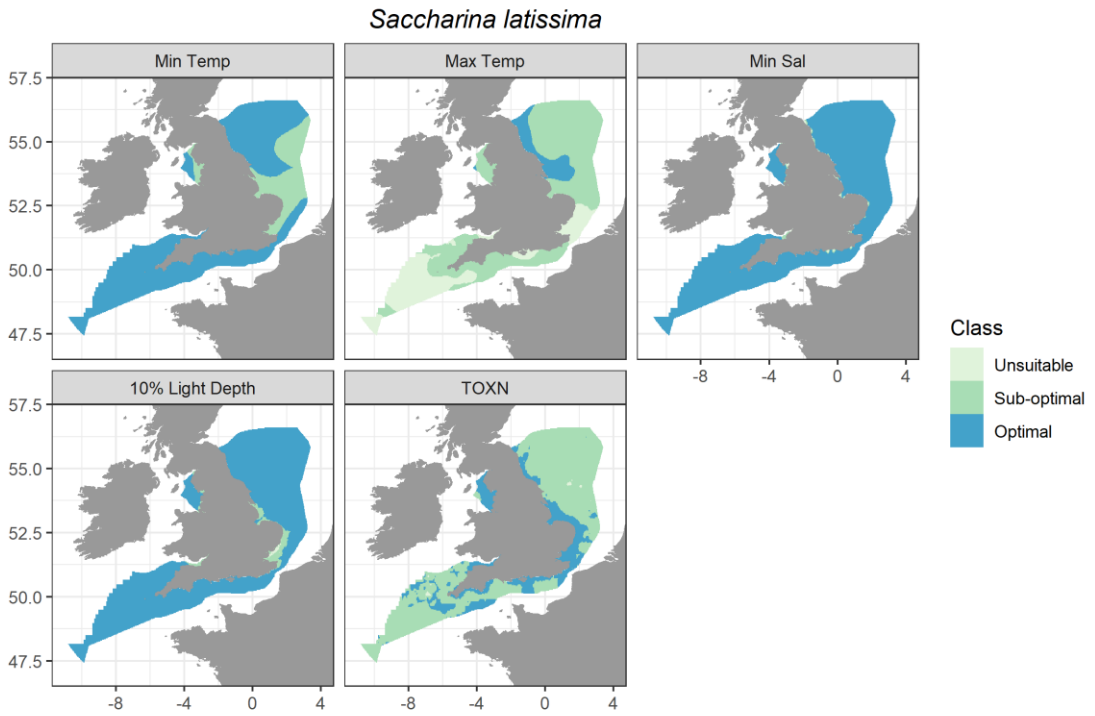
Dissolved Oxygen

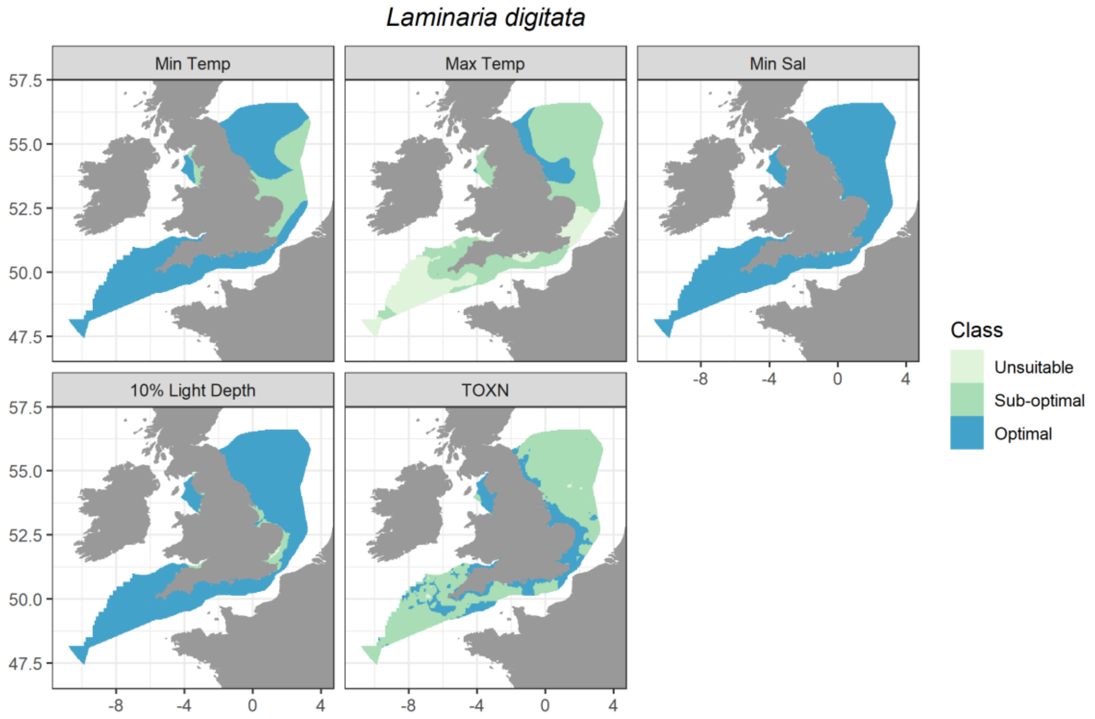


TOxN

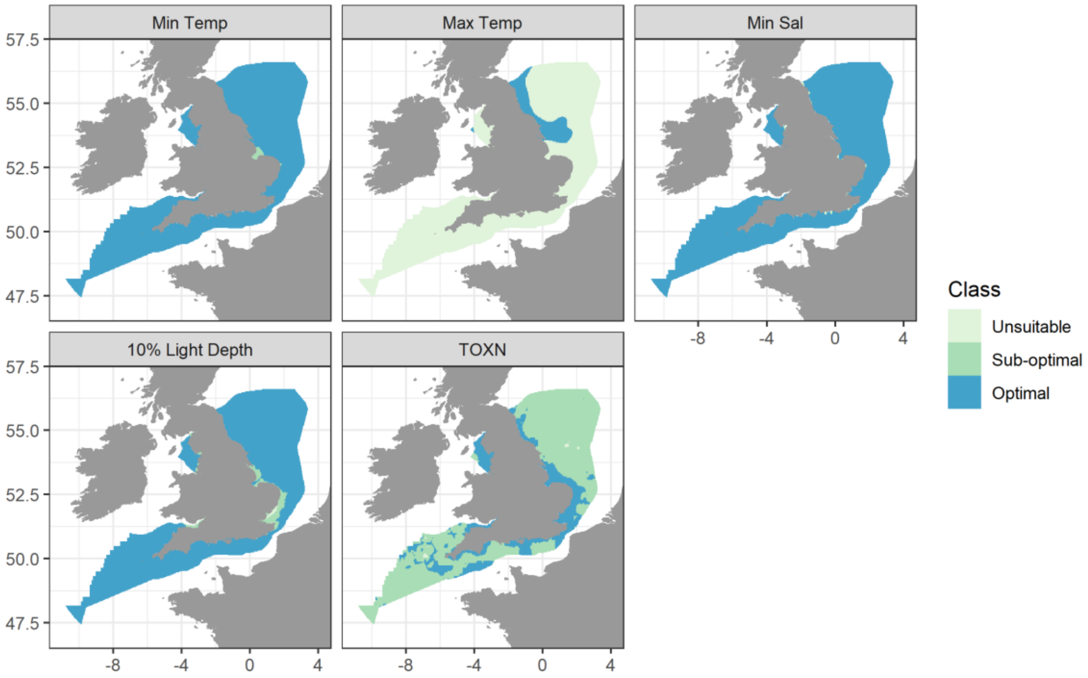
	
Light Penetration	**Chlorophyll**
	
Current Speed	**Wave Height**
	
Bathymetry	**Substrate**

Annex A2. Classified Environmental Layers

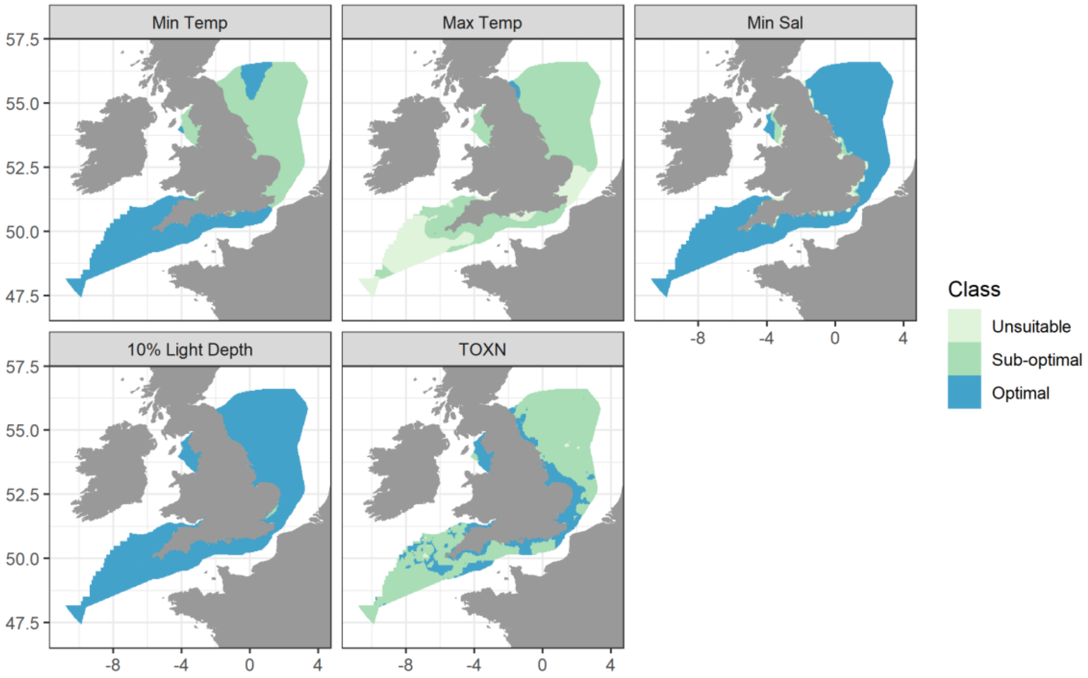


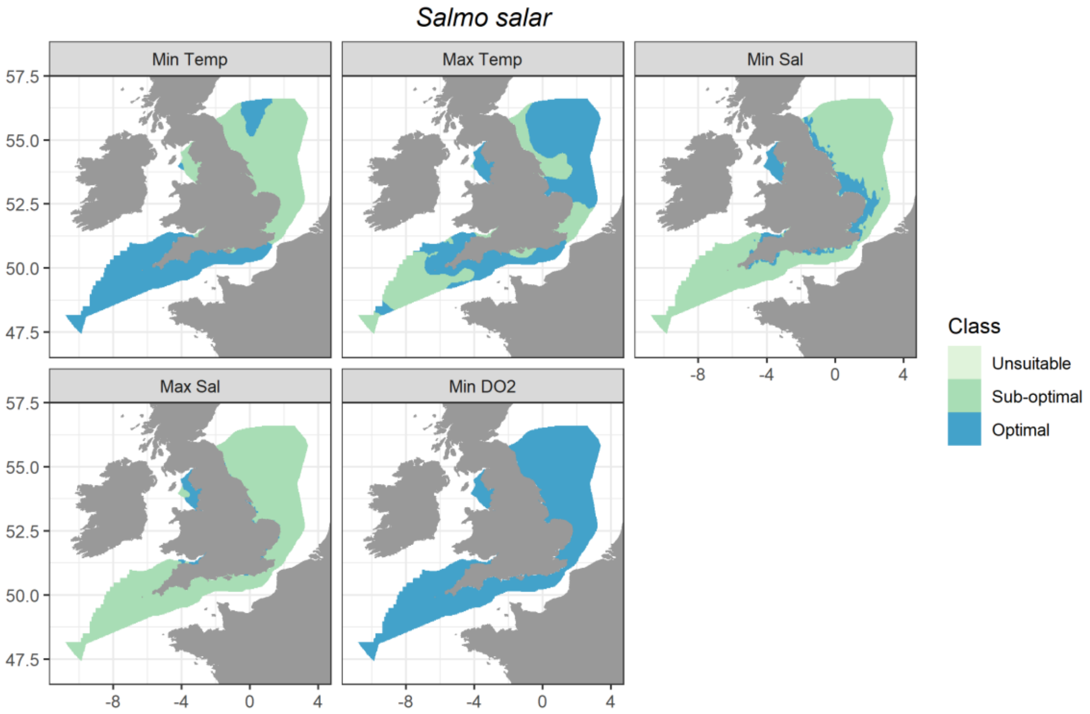


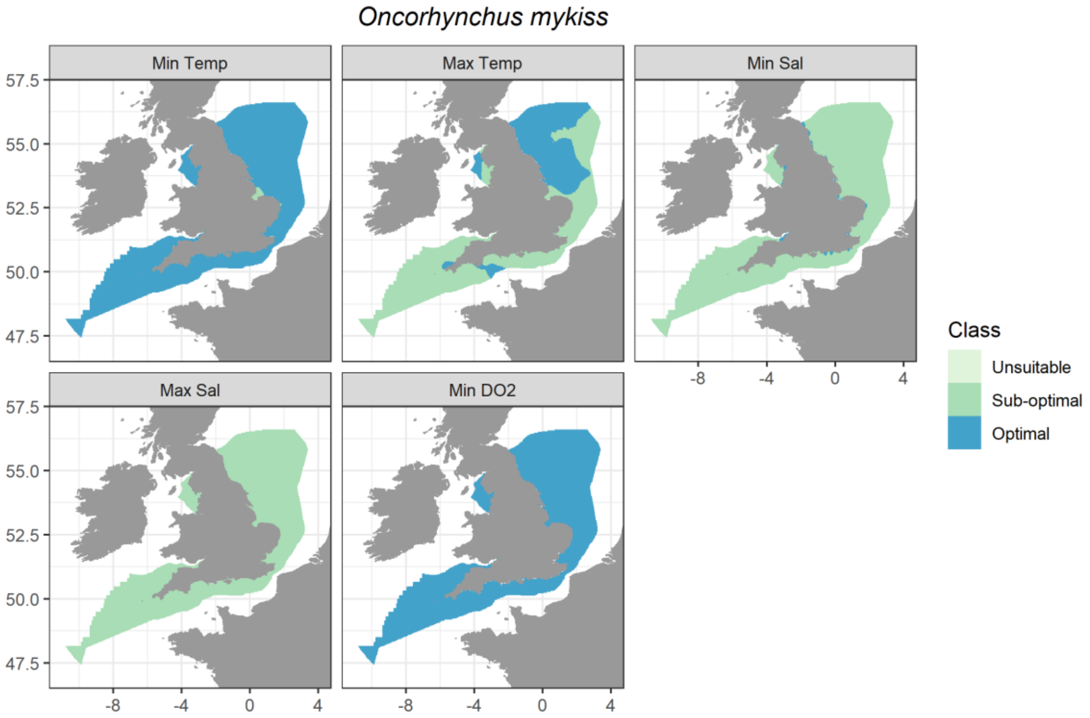
Alaria esculenta

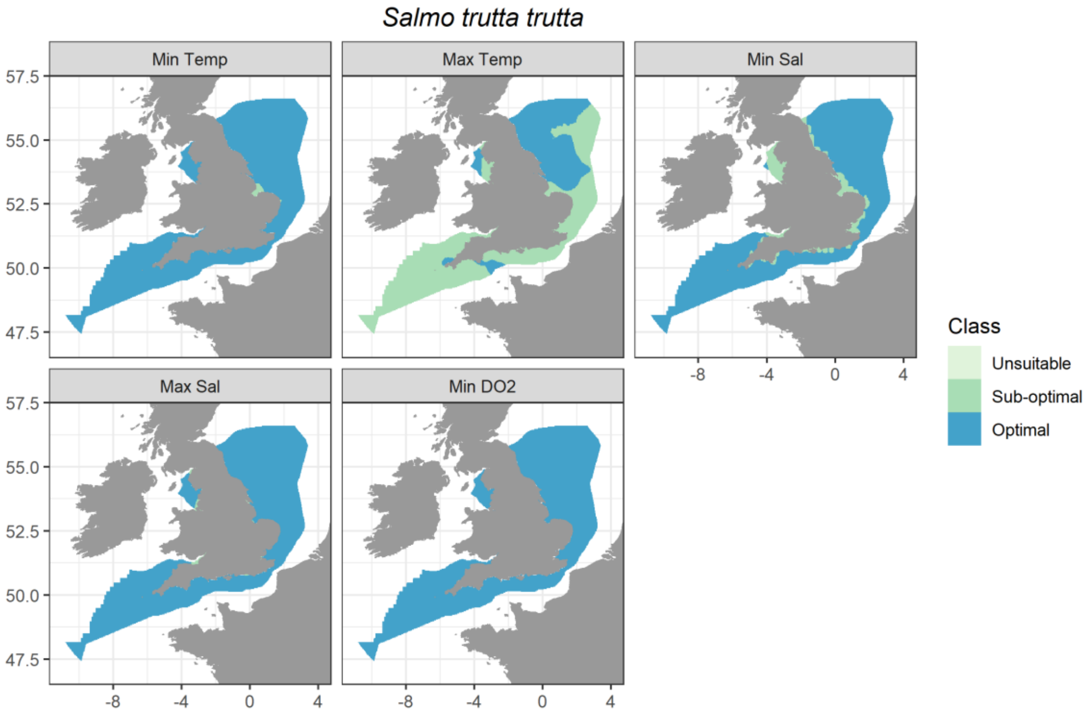


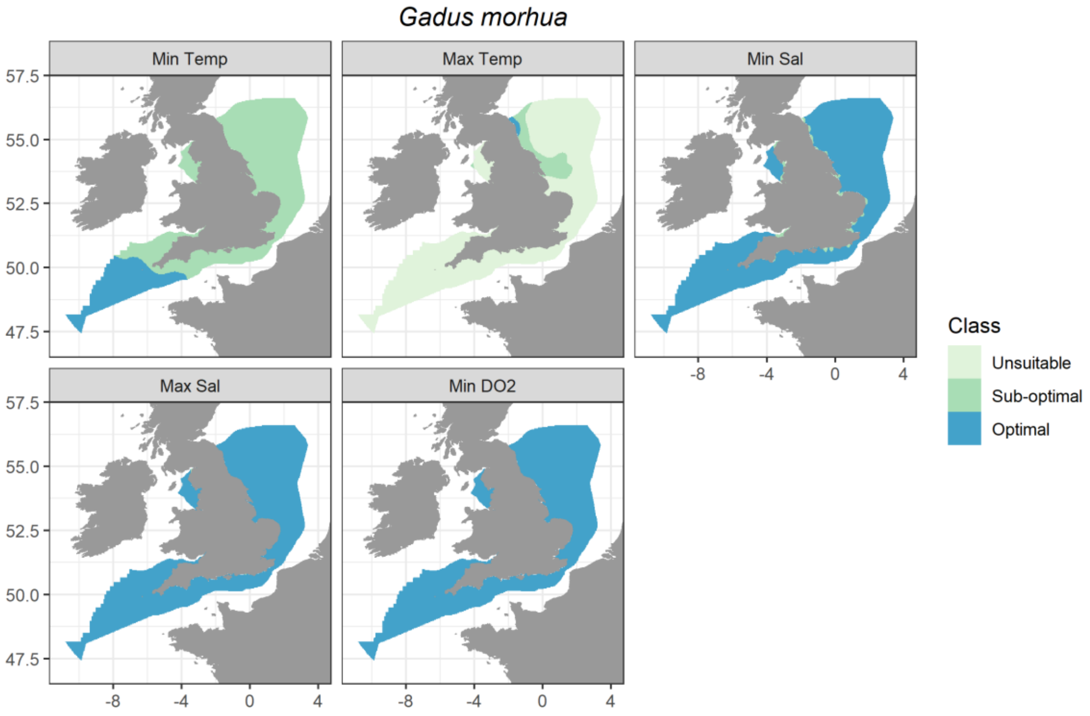
Palmaria palmata

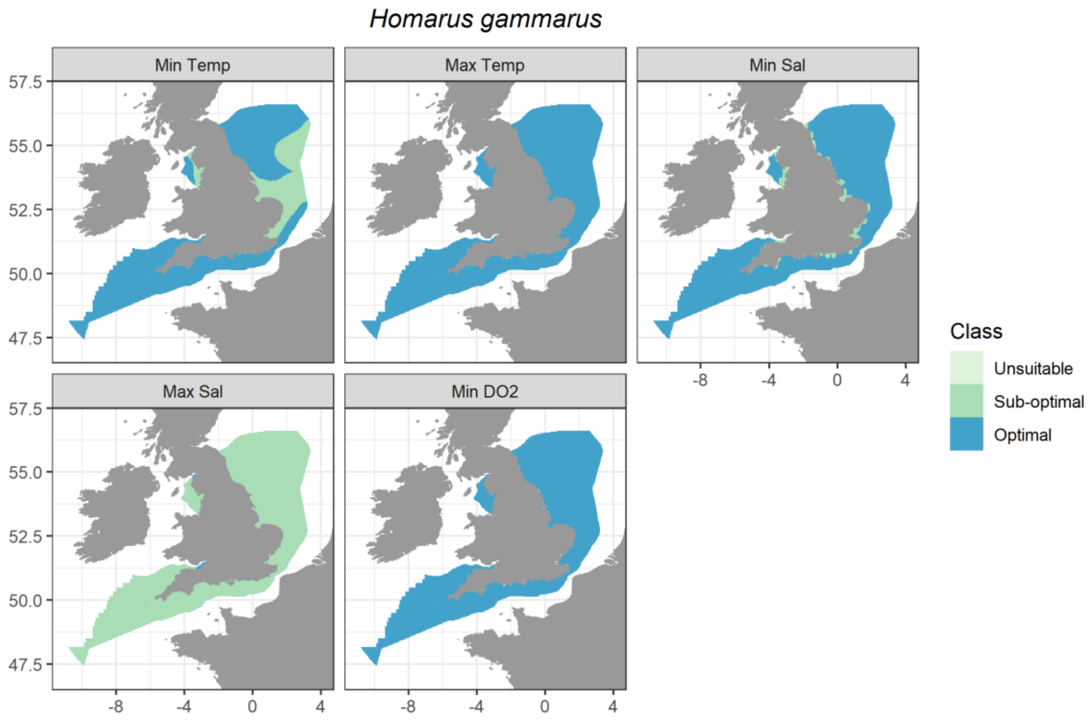


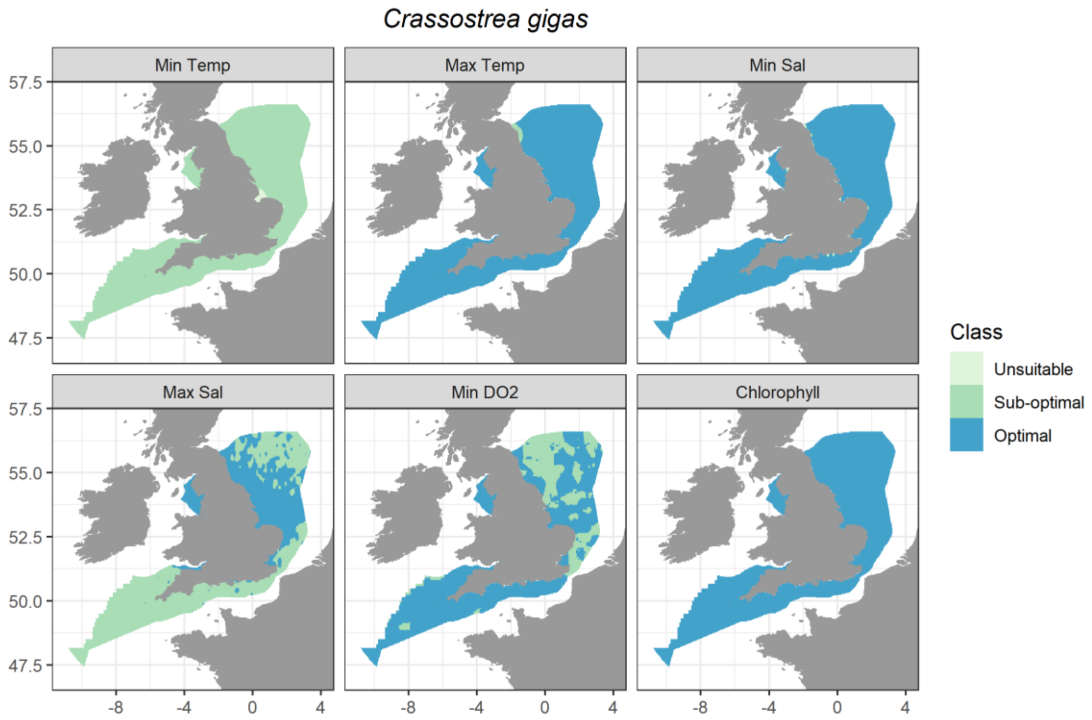

Salmo salar
Min Temp
Max Temp
Min Sal
Max Sal
Min DO2
57.5
55.0
52.5
50.0
47.5
-8
-4
0
4
Class
Unsuitable
Sub-optimal
Optimal

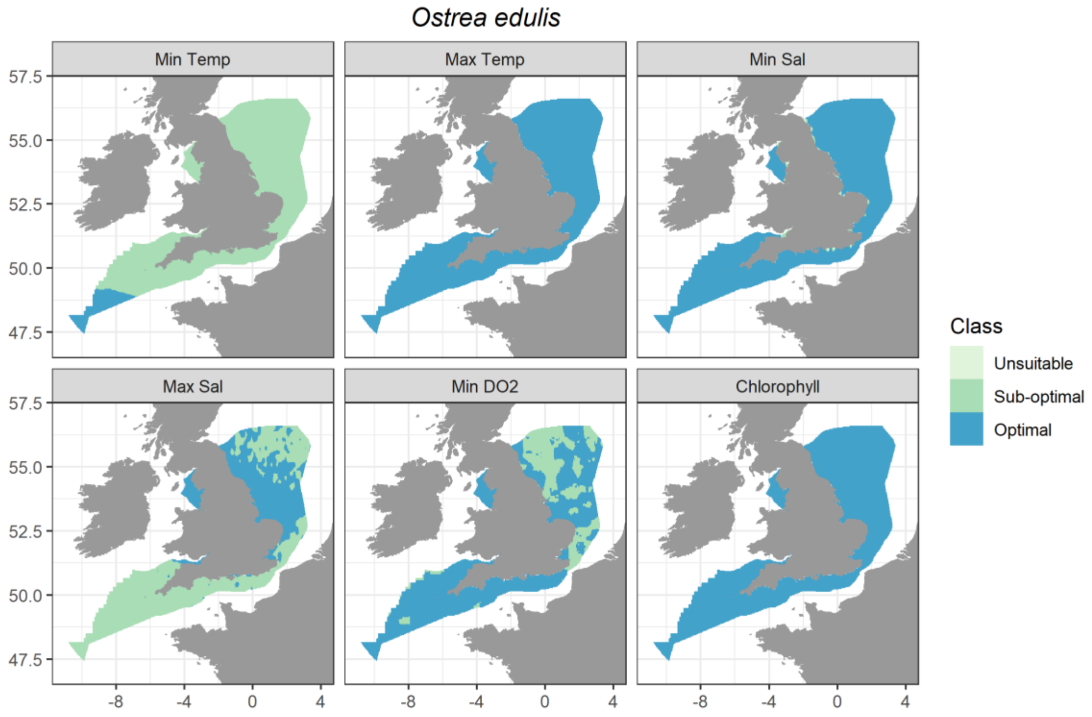

Oncorhynchus mykiss
Min Temp
Max Temp
Min Sal
Max Sal
Min DO2
57.5
55.0
52.5
50.0
47.5
-8
-4
0
4
Class
Unsuitable
Sub-optimal
Optimal

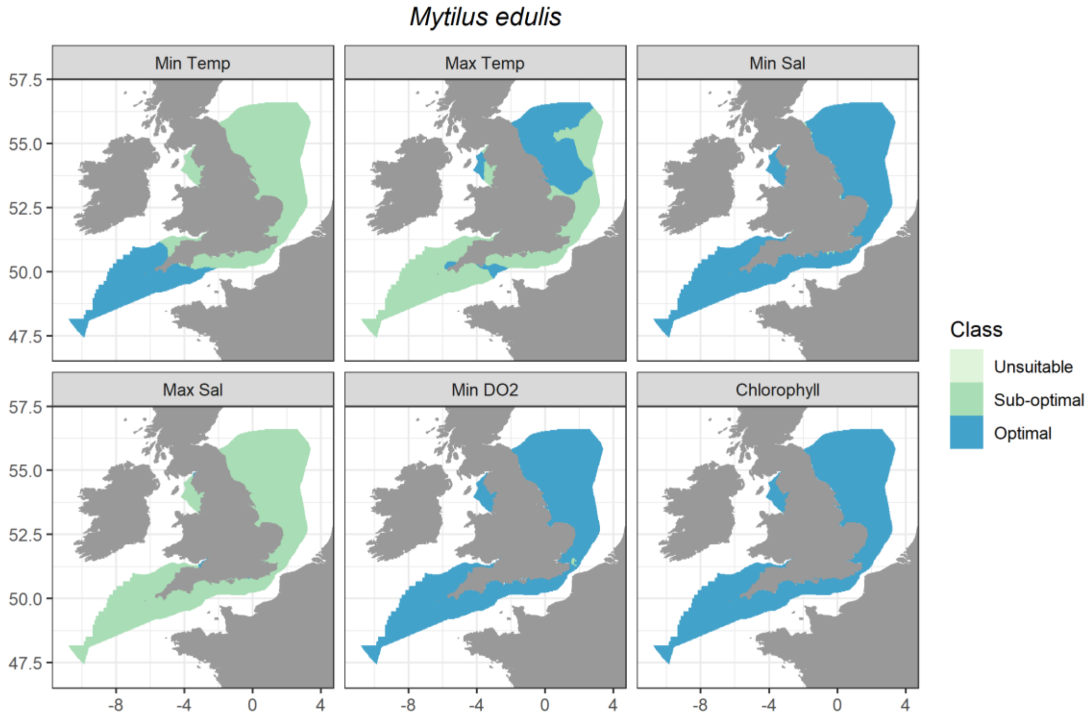

Salmo trutta trutta
Min Temp
Max Temp
Min Sal
Max Sal
Min DO2
57.5
55.0
52.5
50.0
47.5
-8
-4
0
4
Class
Unsuitable
Sub-optimal
Optimal

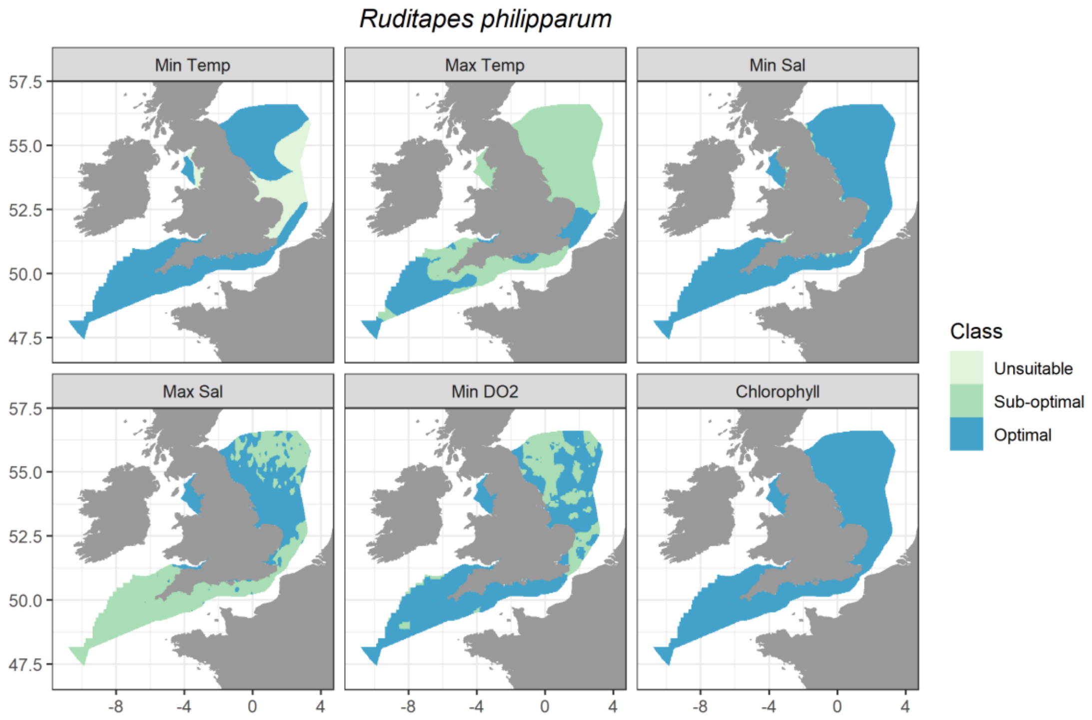

Gadus morhua
Min Temp
Max Temp
Min Sal
Max Sal
Min DO2
57.5
55.0
52.5
50.0
47.5
-8
-4
0
4
Class
Unsuitable
Sub-optimal
Optimal

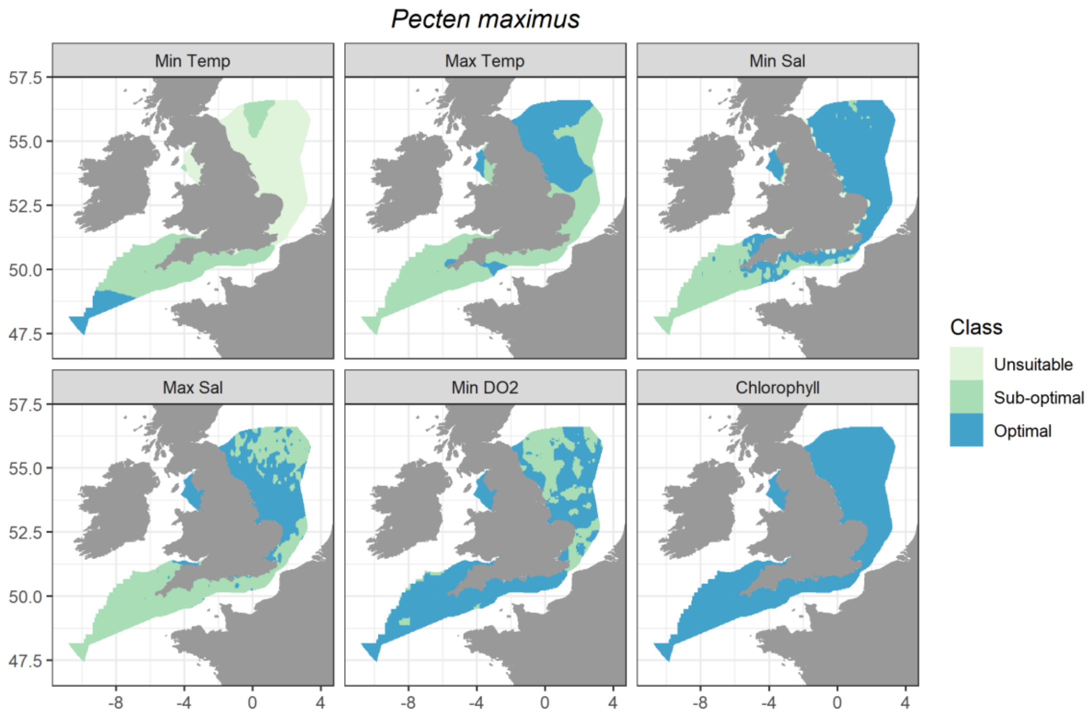

Homarus gammarus
Min Temp
Max Temp
Min Sal
Max Sal
Min DO2
57.5
55.0
52.5
50.0
47.5
-8
-4
0
4
Class
Unsuitable
Sub-optimal
Optimal


Crassostrea gigas
Min Temp
Max Temp
Min Sal
Max Sal
Min DO2
Chlorophyll
57.5
55.0
52.5
50.0
47.5
-8
-4
0
4
Class
Unsuitable
Sub-optimal
Optimal


Ostrea edulis


Mytilus edulis


Ruditapes philipparum
Min Temp
Max Temp
Min Sal
Max Sal
Min DO2
Chlorophyll
57.5
55.0
52.5
50.0
47.5
-8
-4
0
4
Class
Unsuitable
Sub-optimal
Optimal


Pecten maximus
Min Temp
Max Temp
Min Sal
Max Sal
Min DO2
Chlorophyll
57.5
55.0
52.5
50.0
47.5
-8
-4
0
4
Class
Unsuitable
Sub-optimal
Optimal