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A global assessment of offshore mariculture potential from a spatial perspective

Cover illustrations:
Map: Areas (dark blue) within Exclusive Economic Zones with temperatures favourable for offshore grow-out of cobia, *Rachycentron canadum.*
Photo: Cobia in submerged Aquapod net pens at the former site of Snapperfarm, Puerto Rico (courtesy of Ocean Farm Technologies Inc.).

A global assessment of offshore mariculture potential from a spatial perspective

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Preparation of this document

There is growing need to transfer land-based and/or coastal aquaculture production systems further into the sea as a result of the expected increases in human population, competition for access to land, and clean water needed to increase the availability of fish and fishery products for human consumption. Mariculture, in particular offshore aquaculture, offers significant opportunities for sustainable food production and for the development of many coastal communities, especially in regions where the availability of land, nearshore space and freshwater are limited.

This technical paper is an expanded and more detailed version of a contribution entitled "Spatial analysis of the potential for offshore mariculture" to a Food and Agriculture Organization of the United Nations (FAO) workshop proceedings (Lovatelli, Aguilar-Manjarrez and Soto, forthcoming) that aims at providing additional guidance in the development of offshore mariculture. The workshop proceedings collect and synthesize global information on the potential for offshore mariculture development by focusing on technical, environmental, spatial and governance challenges. The goal is also to identify major opportunities and challenges that FAO, its Member States and other stakeholders could act upon for the industry to grow on a sustainable footing.

This technical paper responds to the needs of the FAO Member States in providing estimates of the potential for offshore mariculture development, presenting, for the first time, quantitative spatial measures of the status and potential of offshore mariculture development that are comprehensive of all maritime nations and comparable among them.

This document is part of a recent series of spatially oriented activities aimed at the development and management of aquaculture. These activities have included reviews on geographic information systems, remote sensing and mapping for marine aquaculture, and spatial planning tools to support the ecosystem approach to aquaculture. Additionally, the activities also cover marine spatial planning for aquaculture, site selection and carrying capacity, and virtual technology and decision-support tools. Although these activities have had varying objectives, the common theme among them is the demonstration of the essential role of spatial analysis in the development and management of aquaculture from global to local levels. The present document continues this theme.

Abstract

Mariculture accounts for about one-half of total aquaculture production by weight. About one-half of the mariculture production consists of aquatic plants, with the remainder being fish and invertebrates. Nearly all of mariculture is inshore. In contrast, offshore mariculture, which is practised in the open sea with significant exposure to wind and wave action and with equipment and servicing vessels operating in severe sea conditions from time to time, is in its infancy and production is almost exclusively of fish and shellfish. There is an impetus for mariculture to move to the unprotected waters of the open sea. Issues at the local level include competition for space, water quality problems, and a negative public perception of mariculture's environmental and aesthetic impacts. At the global level, there is concern for food security with expanding population along with the conviction that the potential of the world's oceans to supplement the food supply is vastly underutilized. Prospecting for suitable locations is a critical part of spatial planning for offshore mariculture's near-future development. Thus, the objectives of this technical paper are to provide measures of the status and potential for offshore mariculture development from a spatial perspective that are comprehensive of all maritime nations and comparable among them, to identify nations not yet practising mariculture that have a high offshore potential for it, and to stimulate interest in detailed assessments of offshore mariculture potential at national levels.

Estimates of offshore mariculture potential are based on key assumptions about its near-future development: offshore mariculture will develop within exclusive economic zones (EEZs), will mainly use culture systems modified from inshore mariculture, and will mainly employ species with already proven culture technologies and established markets. These assumptions set the stage for the identification of analytical criteria. Thus, EEZs were used as spatial frameworks to define the limits of national offshore mariculture development. Potential was defined by the depth and current speed limits on offshore cages and longlines, the cost-effective area for offshore mariculture development, and the favourable conditions for grow-out of representative species: cobia (*Rachycentron canadum*), Atlantic salmon (*Salmo salar*) and blue mussel (*Mytilus edulis*), and integrated multitrophic aquaculture (IMTA) of the last two species. Verification and comparison with existing mariculture showed that, despite the limitations of the data, the results are indicative of offshore mariculture potential within the specified criteria.

Offshore mariculture potential is large. At present, 44 percent of maritime nations with 0.3 million kilometres of coastline are not yet practising mariculture. About half of the mariculture nations have outputs of less than 1 tonne/kilometre of coastline. About one-half of inshore mariculture production consists of aquatic plants, but there is little production of plants offshore. Scenarios using 5 and 1 percent of the area meeting all of the criteria for each of the three species showed that development of relatively small offshore areas could substantially increase overall mariculture production. Improvements in culture technologies allowing for greater depths and increased autonomies, as well as the further development of free-floating or propelled offshore installations, would add greatly to the area with potential for offshore mariculture development.

Remote sensing for the sustainable development of offshore mariculture is included as Annex 3 to this publication in recognition of the importance of remote sensing as a source of data for spatial analyses to assess potential for offshore mariculture, and also for zoning and site selection as well as for operational remote sensing to aid mariculture management.

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Abbreviations and acronyms

CHL-2	Chlorophyll-*a* concentration estimated by algorithms that deal with the effects of suspended solids and dissolved organic matter that occur in coastal waters cm/s centimetres per second
CCRF	FAO Code of Conduct for Responsible Fisheries
cs	current speed
EA	ecosystem approach
EAA	ecosystem approach to aquaculture
EEZ	exclusive economic zone
ESRI	Environmental Sciences Research Institute
FAO	Food and Agriculture Organization of the United Nations
FCR	food conversion ratio
GADM	Database of Global Administrative Areas
GEBCO	General Bathymetric Chart of the Ocean
GIS	geographic information systems
GISFish	Global Gateway to Geographic Information Systems, Remote Sensing and Mapping for Fisheries and Aquaculture
GMFMC	Gulf of Mexico Fishery Management Council
HYCOM	HYbrid Coordinate Ocean Model
IMTA	integrated multitrophic aquaculture
ITCZ	Intertropical Convergence Zone
IUCN	International Union for Conservation of Nature
nm	nautical mile
OECD	Organisation for Economic Co-operation and Development
OHI	Ocean Health Index
MPA	marine protected areas
NMFS	National Marine Fisheries Service
SST	sea surface temperature
SWH	significant wave height
UNEP	United Nations Environment Programme
TGC	thermal growth coefficient
VBA	Visual Basic for Applications
VLIZ	Flanders Marine Institute
WCMC	World Conservation Monitoring Centre

Executive summary

Why mariculture needs to move offshore

Mariculture, with a production of 36.1 million tonnes and a value of US$37.9 billion in 2010 (FAO Statistics and Information Branch of the Fisheries and Aquaculture Department, 2012), accounts for about one-half of total aquaculture production by weight. About one-half of the mariculture production consists of aquatic plants, with the remainder being fish and invertebrates. Nearly all of mariculture is inshore mariculture, that is mariculture that is situated or carried out near the shore. In contrast, offshore mariculture practice is in its infancy and production is almost exclusively of fish and shellfish. Drivers at local and global levels provide impetus for mariculture to move to the unprotected waters of the open sea. At the local level, there are issues of competition for space both within the mariculture sector and with other users, problems with water quality, and oftentimes there is a negative public perception of mariculture's environmental and aesthetic impacts. At the global level, there is concern for maintaining food security with expanding population. Also, there is the conviction that the potential of the world's oceans to supplement the food supply is vastly underutilized. This situation places a premium on spatial planning for offshore mariculture. Prospecting for suitable locations for offshore mariculture's near-future development is a critical part of a future-focused approach that will take advantage of opportunities for increasing production while minimizing the issues associated with inshore mariculture.

A framework for offshore mariculture development

Recognizing the need to stimulate the development of offshore aquaculture, the FAO Fisheries and Aquaculture Department conducted a workshop on offshore mariculture (Lovatelli, Aguilar-Manjarrez and Soto, forthcoming). The workshop recognized that FAO can guide and support its Member States and the industry as a whole in the policy and technical developments needed for expanding mariculture to offshore areas. As part of this framework, spatially derived estimates are essential to define locations and quantify expanses of areas suitable for offshore mariculture development. Furthermore, many of the issues and opportunities associated with the development of offshore mariculture have components that can be addressed separately, or together, using spatial analyses. In particular, spatial analysis lends itself to the integration of technical, economic, environmental and jurisdictional problems of mariculture development, all of which are included in this study.

Objectives of this technical paper

The main objective of this technical paper is to provide measures of the status and potential for offshore mariculture development from a spatial perspective that are comprehensive of all maritime nations and comparable among them. The results are a spatial gauge of the indicative near-future global and national potential for the expansion of mariculture from the present inshore locations to offshore areas. The results are also aimed at stimulating much more comprehensive and detailed assessments of offshore mariculture potential at national levels. A final objective is to identify nations that have a high offshore mariculture potential but that are not yet practising it.[1] With these objectives in mind, the study is aimed at decision-makers of

[1] Mariculture countries for the purposes of this study are those listed in the FAO aquaculture production statistics (FAO Statistics and Information Branch of the Fisheries and Aquaculture Department, 2010) as having mariculture production originating from the marine environment in one or more years for the period 2004–2008.

international organizations and at all levels of governmental administrations involved with aquaculture development as well as at entities in the commercial sector involved with mariculture services and development.

How offshore mariculture potential was estimated and verified

The process began with key assumptions about the near-future development of offshore mariculture. Among the key assumptions are that offshore mariculture will develop within the exclusive economic zones (EEZs), will mainly use cages for fish and longlines for molluscs modified for offshore conditions, and will mainly employ species with already proven mariculture technologies and established markets. These assumptions set the stage for the establishment of analytical criteria and thresholds that are at the core of the spatial analyses. The analytical criteria and corresponding thresholds that define the technical limits on cages and longlines are depths (25–100 m) and current speeds (10–100 cm/s). Likewise, the criteria that define the cost-effective area for development of offshore mariculture are cost limits on travel time and distance from shore to offshore installations (25 nm, or 46.3 km), and reliable access to a port. Species indicative of various kinds of mariculture potential and that meet the culture system technology and market requirement criteria are cobia, Atlantic salmon and blue mussel. Favourable grow-out of fish and mussels is defined by water temperature (22–32 ºC for cobia, 1.5–16 ºC for Atlantic salmon, and 2.5–19 ºC for blue mussel). In the case of the blue mussel, favourable grow-out also is assessed by food availability measured as chlorophyll-*a* concentration (> 0.5 mg/m^3). Potential for offshore integrated multitrophic aquaculture (IMTA) of the last two species also was analysed. Spatial analyses were carried out using a geographic information system (GIS). Offshore mariculture potential was reported as maps showing the areas with potential, tables that presented surface areas in aggregate globally, and charts with potential ranked by nations.

The results were verified by comparisons of national-level production of each of the three species with national-level offshore mariculture potential, locations of inshore mariculture with offshore potential at national and local levels, and offshore mariculture locations compared with offshore potential in the same areas. The verification and comparison exercises showed that, despite the limitations of the data, the results are sufficiently reliable for the objectives, namely to comprehensively and comparatively deliver locations and surface areas of offshore mariculture potential aggregated globally that are a first approximation of near-future offshore mariculture potential at the national level.

Near-future offshore mariculture potential

Estimates of near-future mariculture potential come from two perspectives. The first is the assessment of the present status of mariculture in spatial terms covering the period 2004-2008. The results of this assessment indicate that the global potential is large for both inshore and offshore mariculture in aggregate and for many nations individually for the following reasons: nearly all of present-day mariculture takes place in sheltered areas, not offshore. Interestingly, about 44 percent of maritime nations are not yet practising mariculture; about one-half of mariculture production consists of aquatic plants, but there is as yet little production of plants offshore. Mariculture intensity measured as production in terms of tonnes/kilometre of coastline reveals that there are 0.3 million km of coastline along which mariculture is not yet practised. Mariculture intensity is highest in the Northern Temperate Zone followed by the Intertropical Convergence Zone, the Arctic Zone and the Southern Temperate Zone. Among the 93 nations and territories already practicing mariculture, 51 percent produce at a relatively low intensity of less than 1 tonne/kilometre of coastline.

The second perspective is based on spatial integration of basic criteria for cage and longline culture systems (depth, current speed) with criteria for favourable grow-out of cultured animals (temperature, food availability as chlorophyll-*a* for the mussel).

- There are large areas globally among many nations with potential for development of offshore mariculture. Overall potential (i.e. without taking into account distance from shore) for cobia is 793 938 km^2, for Atlantic salmon 30 566 km^2, for blue mussel 29 960 km^2, and for IMTA 14 590 km^2. This approximates potential for other fish and mussel species with similar environmental requirements for grow-out in cages or on longlines.
- Even when further constrained by including the cost-effective area for development as an additional criterion, large areas with potential that include many nations remain. Offshore potential for Atlantic salmon (2 447 km^2) and blue mussel (5 848 km^2) is limited to the nations already practising their culture in inshore waters. Potential for IMTA of these species is 1 202 km^2. In contrast, offshore mariculture potential for cobia is 97 192 km^2 among 80 maritime nations, of which 34 are not yet practising mariculture. This indicates that there is greater offshore mariculture potential for species with warm temperate and tropical grow-out regimes than for those with cool and cold temperate grow-out regimes.
- Mariculture potential has been assumed with other uses of marine space set aside. However, marine protected areas have been used as an illustration of possible competing, conflicting or complementary uses. This is a reminder that, although the area with potential is large, that potential will be reduced considerably by alternative uses for the same marine space, especially in inshore areas where current marine activities are focused.
- A fundamental question is how much area is sufficient for offshore mariculture development that would contribute to the global food supply? Development scenarios using 5 and 1 percent of the area meeting all of the criteria for each of the three species indicated that development of relatively small offshore areas could substantially increase overall mariculture production.
- Improvements in technologies could considerably increase offshore mariculture potential. The area meeting depth, current speed and cost-effective area for development criteria is only 0.1 percent of the total EEZ area. For instance, an increase in the mooring system depth for cages and longlines from the 100 m limit used herein to 150 m would increase the suitable area by 31 percent, or 4.2 million km^2. Looking to a more distant future, free-floating and propelled offshore culture installations would potentially open immense areas to offshore farming that would still be within EEZs, nearly 158 million km^2 for a structure requiring a minimum depth of 25 m.

Policy implications for offshore mariculture development

Policy implications for offshore mariculture development are considered as those pertaining to FAO, and possibly to other international organizations providing technical assistance, and to maritime nations.

Policy implications for FAO

- A significant number of maritime nations are not yet practising mariculture, let alone offshore mariculture. This suggests the need for a proactive approach by FAO that would be a rapid appraisal (desk study) to determine the reasons for the lack of development and to make recommendations on steps that should be taken to stimulate mariculture development among the most promising nations. The results of the present study identify the non-mariculture nations ranking highly in offshore mariculture potential and provide one of the starting points for the appraisal.

- It will be important to monitor the growth of the offshore mariculture industry. For this purpose, FAO and Member countries will need to create a new aquaculture statistical category "offshore mariculture". Underlying that is the need for a simple, spatially oriented but unambiguous, definition for offshore mariculture.
- Spatial planning for offshore mariculture should be considered as one of the components of marine spatial planning.
- FAO is in a position to provide strong worldwide leadership for more holistic development of offshore mariculture that must comprise the full range of components identified under the FAO Code of Conduct for Responsible Fisheries and the ecosystem approach to aquaculture (EAA).
- There is a continuing need to gauge capacities (human resources, infrastructure, finances) at the national and/or regional level to implement the use of appropriate modelling and spatial tools in support of offshore mariculture development so that capacity-building initiatives can be matched to existing capabilities.
- The investigation of aquaculture potential need not be confined to marine environments. A similar approach could be used to investigate and further plan for aquaculture in all environments for nations that have not already done so.

Policy implications for maritime nations

- Maritime nations not yet practising mariculture, particularly those for which this study signals relatively large potential, should consider a broad-based rapid appraisal of opportunities and impediments for mariculture development.
- Nations already practising mariculture should consider undertaking a thorough appraisal of their offshore mariculture potential that would be couched in the EAA. Ideally, the appraisal would be designed so that the results would also satisfy broader efforts for marine spatial planning.
- An important goal of spatial analysis is to locate and quantify the complementary uses while avoiding or minimizing the competing and conflicting uses. This study, in a very broad way, serves to indicate the spatial domains that could become offshore mariculture uses as a component in marine spatial planning at regional and national levels.

Introduction

The introduction is in two parts. The first part deals with the rationale and goals of the study. The second part is an overview of the analytical approach and main data sets.

1.1 Background and objectives

Global mariculture production totalled 36.1million tonnes with a value of US$37.9 billion in 2010 (FAO Statistics and Information Branch of the Fisheries and Aquaculture Department, 2012). Mariculture is an important part of aquaculture, accounting for about one-half in production by weight. Nearly all of global mariculture is actually inshore mariculture that is mariculture that is situated or carried out near the shore. For example, a Google Earth-based study of the spatial distribution of fish cages and pens among 16 countries in the Mediterranean showed that 80 percent of these installations were within 1 km of the coast and that the maximum distance offshore was about 7 km (Trujillo, Piroddi and Jacquet, 2012). Generally, inshore mariculture production is well established in protected coastal locations, in shallow waters with low hydrodynamic energy, and in areas that are in close proximity to supporting infrastructure (Olsen *et al.*, forthcoming). Mariculture production consists of fish, invertebrates and aquatic plants, with the plants accounting for about one-half of the weight. In contrast, offshore - or open ocean mariculture - is in its infancy and production is almost exclusively made up of fish and shellfish. Mariculture is moving offshore using two approaches: one of which is the development of more robust versions of existing inshore culture technologies, and the other of which is through the development of novel culture systems that can be submerged to avoid the winds and waves characteristic of offshore areas (Jeffs, forthcoming).

A number of definitions have been proposed for offshore aquaculture, and the problem of defining the term "offshore" in relation to mariculture development has been discussed at length by Lovatelli, Aguilar-Manjarrez and Soto (forthcoming). However, for the purposes of this technical paper, the definition proposed by Drumm (2010) (Box 1) is adequate and is consistent with the assumptions and criteria for offshore mariculture development set out in Section 1.2.

BOX 1

Definition of offshore aquaculture

"In general Offshore Aquaculture may be defined as taking place in the open sea with significant exposure to wind and wave action, and where there is a requirement for equipment and servicing vessels to survive and operate in severe sea conditions from time to time. The issue of distance from the coast or from a safe harbour or shore base is often but not always a factor".

Source: Drumm (2010).

At local and national levels, the drivers for the expansion of mariculture from existing inshore areas to offshore waters are the competition for space, frequent negative public perception and quality of the environment. Looking to the future, the development of offshore mariculture can be justified on the basis of the need to provide food security in the face of the projected increase of world population. Viewing the oceans as contributing to future food security is in line with the conviction that the potential of the world's oceans to supplement the food supply is vastly underutilized (inter alia, Forster, 2007). As pointed out by Forster (2011a; forthcoming), only 1.7 percent of the world's total food tonnage comes from the ocean, an area covering about 70 percent of the Earth. Of that, less than 0.5 percent is from mariculture.

There has been interest in expanding aquaculture to offshore areas for decades (for example, Hanson, 1974; Wilcox, 1982; Ryan, 2004; Lee and O'Bryen, 2007a; Benetti and Welch, 2010; Simpson, 2011). Recognizing the need to assess the possibilities for the development of offshore aquaculture, the FAO Fisheries and Aquaculture Department conducted a workshop on offshore mariculture. Thus far, the outputs of the workshop include: workshop proceedings, a global review prepared by Olsen (forthcoming), six technical reviews, and a strategic framework for mariculture development that includes recommended actions by FAO (Olsen *et al.*, forthcoming). The strategic framework recognizes that FAO can guide and support Member States and industry in the development needed for expanding mariculture to offshore locations.

The technical papers presented in the workshop proceedings (Lovatelli, Aguilar-Manjarrez and Soto, forthcoming) include: technical constraints, opportunities and needs to ensure the development of the mariculture sector worldwide in the tropical zone (Jeffs, forthcoming) and in the temperate zone (Forster, forthcoming), a review of environmental and ecosystem issues and future needs for the tropical zone (Angel and Edelist, forthcoming) and for the temperate zone (Holmer, forthcoming), governance in marine aquaculture: the legal dimension (Percy, Hishamunda and Kuemlangan, forthcoming), and mariculture development economics (Knapp, forthcoming). Spatial perspectives on offshore mariculture potential related to the workshop proceedings were presented by Kapetsky and Aguilar-Manjarrez and are summarized in Olsen *et al.*, forthcoming.

Recently, the Aquaculture Forum Bremerhaven conducted a workshop on the future of global open ocean aquaculture development that resulted in the Bremerhaven Declaration (Anon., 2012). The Declaration lays out recommendations and their justifications in nine subject areas. Those most pertinent to this technical paper are a global strategy for sustainable open ocean aquaculture development, the urgent need to plan for the comprehensive development of land- and water-based infrastructures and that priority should be given to the culture of species well-established in aquaculture.

Spatially derived estimates are essential to define locations and quantify expanses of areas suitable by species and culture systems for offshore mariculture development. Furthermore, many of the issues and opportunities associated with the development of offshore mariculture have components that can be addressed separately, or together, using spatial analyses. In particular, spatial analysis lends itself to the integration of technical, economic, environmental and jurisdictional problems of mariculture development, all of which are addressed in this technical paper.

This paper was inspired by the perception that there were few studies dealing specifically with the spatial aspects of offshore mariculture potential, particularly from global and national perspectives. Among the studies addressing the spatial aspects of offshore mariculture at subnational levels, zones suitable for mariculture were identified in the Region of Murcia, the Kingdom of Spain, using water depths between 35 and 50 m and distances that extend up to 15 km from the shore as basic criteria while considering other uses (Servicio de Pesca y Acuicultura, 2000). In a similar study, zones suitable for mariculture in waters up to 50 m depth were identified for Andalucia, the Kingdom of Spain (Macias-Rivero, Castillo y Rey and Zurita, 2003). Also in the Kingdom of Spain, Pérez, Telfer and Ross (2005) focused on developing a methodology for selecting suitable sites for offshore farming of seabream (*Sparus aurata*) and seabass (*Dicentrarchus labrax*) in floating cages in Tenerife Island, Canary Archipelago. A preliminary analysis of coastal zone management issues (e.g. fisheries, salmon culture, ecologically sensitive areas) related to the feasibility of open ocean farms in the Bay of Fundy, Canada, was made by Chang, Page and Hill (2005). A first step towards assessing potential sites for offshore aquaculture development in western Ireland was based on a minimum depth of 20 m, shelter from ocean swell and proximity to landing facilities. Of the 46 sites evaluated, at the five most promising sites depth ranged from 27 to 40 m, distance to landing facilities ranged from 6 to 28 km and shelter ranged from moderately exposed from one cardinal point of the compass to exposed from two cardinal points (Watson and Drumm, 2007).

Longdill, Healy and Black (2008) determined the suitability of offshore open coast locations (from the coast to 100 m water depth) for commercial bivalve culture of the New Zealand (or greenshell) mussel (*Perna canaliculus*) within the Bay of Plenty, New Zealand. Kapetsky and Aguilar-Manjarrez (2007) carried out a reconnaissance study of open ocean aquaculture potential of cobia (*Rachycentron canandum*) in cages and blue mussel (*Mytilus edilus*) on longlines in the eastern exclusive economic zones[1] (EEZs) of the United States of America; they later expanded the study to include Atlantic salmon (*Salmo salar*) and the integrated multitrophic aquaculture (IMTA) of Atlantic salmon with blue mussel within the same EEZ area (Kapetsky and Aguilar-Manjarrez, 2010). Gifford, Benetti and Rivera (2007) explored the development of a Caged Aquaculture Suitability Index dedicated to optimally locating caged aquaculture projects planned for offshore Florida (United States of America), the Commonwealth of Puerto Rico, and the United States Virgin Islands. Rester (2009) and the Gulf of Mexico Fishery Management Council and the National Marine Fisheries Service (2009) selected suitable sites for offshore cage aquaculture in the United States of America portions of the Gulf of Mexico in waters from 25 to 100 m in depth with indigenous fish species in mind; species, however, were not individually analysed. A broadly based study for the development of open ocean shellfish farming in the Bay of Biscay included analyses relating to user conflicts, technologies and operational requirements, a wide range of criteria relating to site selection, market analysis and business models (Mendiola *et al.*, 2012; Mendiola and Galparsoro, forthcoming).

The present study builds on previous experience with spatial analysis of offshore mariculture potential and expands the scope from subnational levels to a global perspective. Thus, the main objective of this study is to provide measures of the status and potential for offshore mariculture development from a spatial perspective that are comprehensive of all maritime nations and comparable among them. The results are a gauge, from a spatial perspective, of the indicative near-future global and national potential for the expansion of mariculture from current inshore locations to offshore areas. The results are also meant to stimulate interest in national-level assessments of mariculture potential, which would include more criteria and higher resolution data than in this technical paper. An additional objective is to identify nations that appear to have high potential but that are not yet practising mariculture.[2] With these objectives in mind, the study is aimed at decision-makers of international organizations and at all levels of governmental administrations involved with aquaculture development as well as at entities in the commercial sector involved with mariculture services and development.

1.2 Overview of the analytical approach and outputs

The objective of this section is to briefly introduce the framework of the analyses without going into the methods in the detail that would be required to repeat the study. For that purpose, the analytical procedures and the data sources are set out in Annex 1.

[1] An exclusive economic zone (EEZ) is a concept adopted at the Third United Nations Conference on the Law of the Sea (1982), whereby a coastal State assumes jurisdiction over the exploration and exploitation of marine resources in its adjacent section of the continental shelf, taken to be a band extending 200 miles from the shore (OECD, 2012).

[2] Mariculture countries for the purposes of this study are those listed in the FAO aquaculture production statistics (FAO Statistics and Information Branch of the Fisheries and Aquaculture Department, 2010) as having mariculture production in one or more years for the period 2004–2008.

This section provides an account of the development of the analytical approach. In a stepwise fashion, key assumptions about the near-future development of offshore mariculture and some of its salient features provide a foundation for the analyses. The key assumptions are used to identify the analytical criteria. With the analytical criteria identified, numerical thresholds for each criterion are established based on mariculture practice, and the thresholds are then used in spatial analysis to identify locations and to quantify area expanses of various kinds of offshore mariculture potential for each maritime nation.

1.2.1 Key assumptions on the spatial development of offshore mariculture

Key assumptions have been made about where and under what conditions the spatial development of offshore mariculture will take place for the next five to ten years. The assumptions are based on the technical characteristics of inshore and offshore culture installations, and on the aquatic animal species grown out inshore and in the relatively few commercial ventures already established in offshore areas. The near-future assumptions are supported by expert reviews (Lovatelli, Aguilar-Manjarrez and Soto, forthcoming) and a synthesis of them (Olsen *et al.*, forthcoming), and/or are the perceptions of the authors of this technical paper (Box 2).

In spatial terms, it is assumed that near-future offshore mariculture development will take place within EEZs and that, initially, offshore sites will be in close proximity to onshore service facilities. That offshore mariculture will be in close proximity to coastlines is due to a variety of technical and economic limitations, all of which relate to the need to tether culture installations to the seafloor, to the costs of maintaining onshore and offshore facilities, and to the requirement for frequent commuting between them (Box 2). Offshore aquatic plant mariculture was not considered here because of a lack of criteria for offshore culture installations for plants.

BOX 2

Key assumptions about the near-future development of offshore mariculture

Near-future offshore mariculture development will:

- mainly take place within exclusive economic zones in order to ensure national governance over development and management and to provide for the legal protection of investors.
- mainly use cages for fish and longlines for molluscs as culture systems:
  - relatively close to coastlines because of the depth-associated costs of tethering culture systems to the seafloor in relatively shallow coastal waters;
  - limited by technical constraints on mariculture system installation, maintenance and endurance related to the depth of tethering.
- be dependent on onshore facilities:
  - to support offshore grow-out installations (e.g. feed, holding seed, storage, maintenance, set-up for processing and transporting harvested animals);
  - protected from storm damage and with reliable access to the offshore grow-out sites;
  - in close proximity to offshore sites in order to minimize distance-related costs of transport services.
- mainly employ species with already proven culture technologies and established markets.
- compete and conflict with some other uses of ocean space, but will be complementary with others.

1.2.2 Criteria and thresholds used to estimate near-future offshore mariculture potential

This section relates the basic criteria on the near-future spatial development of offshore mariculture to the thresholds that are at the core of the estimates of potential for offshore mariculture development. The criteria to estimate offshore mariculture potential (Table 1) follow from the key assumptions about offshore mariculture development set out in Box 2. These criteria are then related to the various kinds of offshore areas that they represent and to the thresholds that pertain to those areas (Table 1).

TABLE 1

Criteria and corresponding threshold ranges used to estimate near-future offshore mariculture potential

Criteria	Areas with offshore mariculture potential	Thresholds
1. Boundaries of the EEZs of sovereign nations.	Area for offshore development within sovereign national legal jurisdictions.	EEZs up to 200 nm (370.4 km) offshore.
2. Depth and current speed as the fundamental criteria characterizing the technical limits of present offshore submerged cage and longline culture systems.	Areas in which it is technically feasible to place culture installations.	Depth for cages and longlines: 25–100 m. Current speed for cages and cultured animals: 10–100 cm/s.
3. Distance offshore from onshore infrastructure related to economic cost limits on transportation and on reliable access from a port to the sea.	Areas in which it is cost-effective to place culture installations based on distance-related costs and on reliable access from shore to sea.	Cost-effective area for development: area within 25 nm (46.3 km) of a port, with ports defined by the World Port Index (2009).
4. Reliable access between shore and offshore facilities assumed; proximity of offshore culture sites to the shoreline not limited tothe cost-effective area for development.	Areas with potential within EEZs, but presently outside of cost-effective areas for development.	All thresholds other than the cost-effective area for development apply.
5. Favourable offshore grow-out environment based on temperature requirements of representative fish and mussels and on food availability measured as chlorophyll concentration for the latter.	Areas with favourable grow-out environments for fish and mussels.	Temperatures: – Cobia: 22–32 °C – Atlantic salmon: 1.5–16 °C – Blue mussel: 2.5–19 °C and Chlorophyll-*a* > 0.5 mg/m^3 – IMTA: 2.5–16 °C and chlorophyll-*a* > 0.5 mg/m^3
6. Competing, conflicting and complementary uses of ocean space.	Areas with potential lost because of competing and conflicting uses of marine space.	Areas with potential for cobia hypothetically excluded from marine protected areas.

EEZ boundaries to define the spatial limits for near-future offshore development

One of the key assumptions is that near-future offshore mariculture will be developed within the EEZs of sovereign nations (Box 2). The boundaries of EEZs, therefore, provide a spatial framework within which to assess the amount of national area with offshore mariculture potential (Table 1). EEZ boundaries were defined using the Flanders Marine Institute (VLIZ) Maritime Boundaries Geodatabase (Flanders Marine Institute, 2012; Annex 1, Table A1.1). Thus, the term "offshore mariculture potential", for the purposes of this technical paper, resides within the area bounded by EEZs, usually from 3 to 200 nm (5.5–370.4 km) from the shoreline. Offshore mariculture potential in this technical paper is expressed quantitatively as the surface area in square kilometres within EEZs in each sovereign maritime nation meeting various fundamental criteria and their associated thresholds (Table 1).

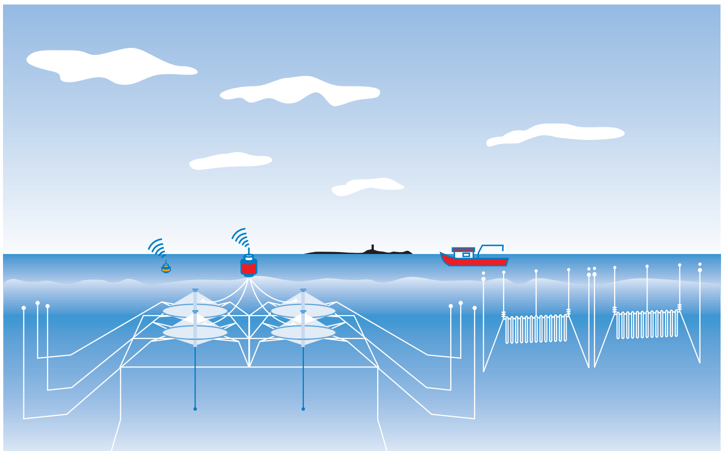
Depth and current speed to define the spatial limits on offshore cages and longlines

Sea cages for fish grow-out and longlines for mussel grow-out are the prevalent culture structures in current offshore mariculture practice (Figure 1). Both sea cages and longlines are tethered to the seafloor. This is the basis for the key assumption that both sea cages and longlines will be located close to coastlines for the near future because of technical and cost limits related to the depth of tethering (Table 1). It assumed that both of these culture systems will be submerged to avoid threatening sea conditions, such as the one depicted in Plate 1, or much worse.

Along with depth, current speed is another fundamental criterion that dictates the offshore space in which sea cages and longlines can be installed (Table 1; Figure 2). Depth affects the size of the seafloor footprint for typical multi-anchor cage systems as well as capital, installation and maintenance costs for the anchoring system (Browdy and Hargreaves, 2009). Current speed affects both the design of offshore installations as well as the growth-related conditions of cultured organisms in or on them in many ways, as shown in Figure 2.

Depth thresholds for sea cages and longlines, 25–100 m (Table 1), were established based on manufacturer specifications and on actual mariculture practice (Annex 1, Table A1.2). Similarly, the current speed threshold (Table 1) was based on the same sources, but also was considered in terms of effects on cultured fish and shellfish (Annex 1, Table A1.3a and A1.3b).

FIGURE 1
Sea cages and longlines for offshore mariculture



Source: NOAA (2011).

FIGURE 2
Effects of current speed on culture structures and on cultured organisms

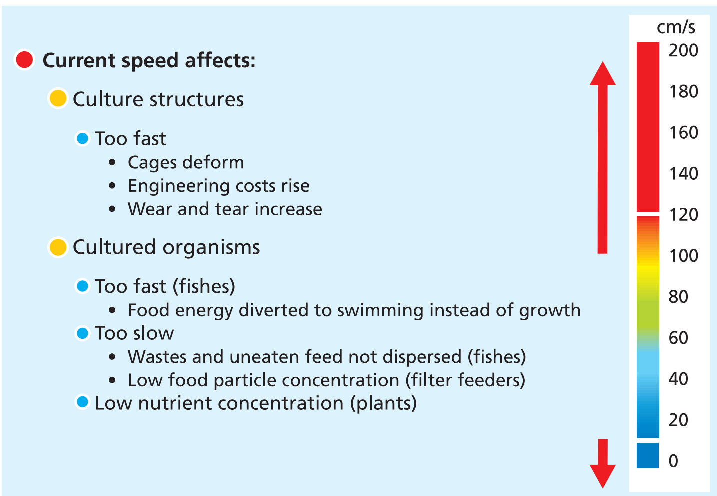


PLATE 1
Fish cages in rough weather in Norway

COURTESY OF AKVA GROUP

Note: Square plastic collar gravity cage in rough conditions, Kingdom of Norway. Polarcirkel, Kingdom of Norway.

Distance from a port and reliable offshore access to spatially define the cost-effective area for offshore mariculture development

A key assumption for near-future offshore mariculture is the dependence, in numerous ways, of offshore development on shoreside support facilities (Box 2; Nash and Fairgrieve, 2007; Lee and O'Bryen, 2007b).

Operational and service activities offshore have their complementary activities at shore support facilities that include, for example, office space, warehousing feed and equipment, and holding facilities for stock destined for grow-out and harvested products. An important aspect of this dependence is the need for offshore installations to be positioned relatively close to onshore facilities so as to minimize distance-related costs of transport and maintenance services. A closely related aspect of this dependence is the need for reliable access from the shore facility to the offshore site in order to carry out routine operations and to deal with emergencies (Box 2). The dependence between the onshore and offshore locations can be defined succinctly as two criteria with which to spatially estimate offshore mariculture potential: the reliable access from shore to offshore and the distance-related costs between shore and offshore (Table 1).

Access from a shore support facility to an offshore mariculture installation was considered an indispensable criterion for assessing potential by Kapetsky and Aguilar-Manjarrez (2007) owing to the numerous operational and service activities that must be carried out on sea cages (e.g. Table 7 in Huguenin, 1997). Access also figures prominently among offshore aquaculture site selection criteria (Benetti *et al.*, 2010). The other criterion, this one with an economic basis, relates to travel time and distance from an onshore support facility to an offshore grow-out installation. Twenty-five nautical miles (46.3 km) was the maximum cost-effective distance from onshore to an offshore culture installation found by Jin (2008) in a study of economic potential of offshore aquaculture operations that included grow-out of Atlantic salmon. The 25 nm (46.3 km) distance has been adopted for this technical paper. The criteria of reliable access and the 25 nm cost-effective distance were combined into a single criterion termed the "cost-effective area for offshore mariculture development". It is defined spatially as the surface area within a 25 nm radius of a port. Ports were those identified in the World Port Index (2009) database (Table 1; Annex 1, Table A1.1).

Offshore mariculture potential within EEZs that is presently outside of cost-effective areas for development

Despite the assumed need to take into account the economic consequences of distance-related costs in estimating potential, there is another near-future situation that must be spatially defined: coastline locations with identified proximate offshore potential but lacking the adjacent ports that have been identified in the World Port Index (2009) database. This has been envisioned in a recent definition of offshore aquaculture (Drumm, 2010; Box 1). It implicitly takes into account the many situations where shoreside facilities and access to the sea are adequate to support offshore installations, but where the World Port Index (2009) database of ports is incomplete. This situation is likely to pertain to developing countries, as well as to developed countries with minor ports. In terms of assumptions and criteria to assess offshore mariculture potential, this situation corresponds to those areas that are technically feasible for offshore mariculture development (i.e. with suitable depths and current speeds for cages and longlines), but outside of the cost-effective area for development (Table 1).

Offshore mariculture potential of three representative species and IMTA of two of them spatially defined by environments favourable for grow-out

The assumption regarding the species that will be important in the immediate future of offshore mariculture states that the species will be mainly those with proven culture technologies and with established markets (Box 2). Many species have been suggested as candidates for mariculture depending on the region of interest, and some of the species are already cultured offshore or are undergoing trials. Including all of the animal species with proven culture technologies and established markets was beyond the scope of this technical paper, and thus three representative species were selected. The species were cobia (*Rachycentron canadum*), Atlantic salmon (*Salmo salar*) and blue mussel (*Mytilus edulis*) (Plate 2).

PLATE 2

Species indicative of different kinds of offshore mariculture potential

COURTESY OF IOUTDOOR

Cobia (*Rachycentron canadum*)

COURTESY OF CORNELL UNIVERSITY

Atlantic salmon (*Salmo salar*)

COURTESY OF NOAA

Blue mussel (*Mytilus edulis*)

Each species is indicative of a different kind of offshore mariculture potential. Criteria for the selection of these species have already been covered by Kapetsky and Aguilar-Manjarrez (2007, 2010), and the same criteria have been employed herein. Multi-country production[3] is indicative of viable technologies and established markets. Global marine mariculture production and value for 2010 were 1.4 million tonnes and US$7.8 billion for the Atlantic salmon, 2 088 000 tonnes and US$349 million for the blue mussel, and 41 000 tonnes and US$71 million for the cobia (FAO Statistics and Information Branch of the Fisheries and Aquaculture Department, 2012). Cobia is among seven fish species in the tropical zone identified by Jeffs (forthcoming) with offshore mariculture potential. Additionally, cobia is currently being cultured in a number of offshore locations (see Chapter 5) and in many inshore locations in the People's Republic of China, the main producing country. An additional advantage that the cobia has over other species is that it has a global distribution. Therefore, its culture offshore for many nations would not involve importing an exotic species. Ryan (2004) and Watson and Drumm (2007) identify open ocean sites for offshore grow-out of Atlantic salmon in Ireland, and Jackson (2007) states that 30 percent of Ireland's farmed salmon come from sites with moderate exposure. Likewise, there are many Atlantic salmon culture sites with partial shelter near the open sea in the Kingdom of Norway (Chapter 5). The blue mussel has been farmed experimentally offshore with encouraging results in the northeastern United States of America (Langan and Horton, 2005; NOAA, 2005) and on a semi-commercial subsidized basis through several initiatives in the same area (Atlantic Marine Aquaculture Center, 2007; Zeiber, 2008). The blue mussel is being assessed for offshore culture in the Federal Republic of Germany in connection with wind farm installations (Buck, 2011).

The species selected as measures of offshore mariculture are representative in several ways of fish and mussels that may eventually figure importantly in offshore mariculture. In this regard, cobia and Atlantic salmon are generic indicators of offshore mariculture potential that are in the category of "fed" mariculture. Both are grown out in sea cages (Plate 3). The blue mussel is indicative of potential for bivalve mussels grown on longlines in cool temperate waters. Being a filter feeder, it exemplifies "extractive" mariculture. This latter criterion enabled estimating potential of not only each of the individual species, but also for estimating the integrated potential of two of them (Atlantic salmon and blue mussel) for potential in IMTA (Figure 3). IMTA has been reviewed from a global viewpoint by Soto (2009).

The three species, taken together, are surrogate indicators of offshore mariculture potential of species with similar temperature thresholds favouring grow-out and, in the case of the mussel, with similar food availability requirements. From a global viewpoint, the growth-temperature

PLATE 3
Example of fed aquaculture of fish in cages

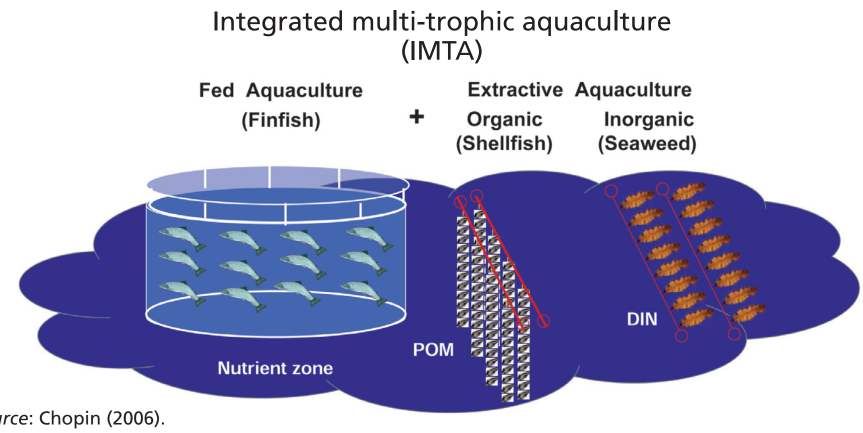
COURTESY OF F. CARDIA

[3] If the fish or shellfish is cultured in several countries, technical expertise and markets are available.

FIGURE 3
Integrated multi-trophic aquaculture in practice and in concept

Salmon (left), mussels (right foreground) and seaweeds (right background) integrated multi-trophic aquaculture (IMTA) in the Bay of Fundy, Canada

Conceptual diagram of an integrated multi-trophic aquaculture (IMTA) operation combining fed aquaculture (finfish) with organic extractive aquaculture (shellfish), taking advantage of the enrichment in particulate organic matter (POM), and inorganic extractive aquaculture (seaweeds), taking advantage of the enrichment in dissolved inorganic nutrients (DIN)



Source: Chopin (2006).

thresholds collectively span all climate zones in which most mariculture takes place: cold and cool temperate for the Atlantic salmon and blue mussel, and tropical and subtropical for the cobia. General information, specifically on the culture of these species, can be obtained through the FAO Cultured Aquatic Species Information Programme (FAO, 2012).

Offshore mariculture potential of these species was based on criteria that could be used to locate areas that would be favourable for grow-out. It is well known that temperature affects the feeding, growth and metabolism of fish and shellfish. Thus, water temperature was the criterion applied to all three species. As an illustration, the apparent effects of water temperature on the duration of grow-out of Atlantic salmon to a harvestable size among four salmon-producing nations are shown in Annex 2. Water temperature, salinity, food quantity and quality are the most important factors affecting grow-out time of mussels (Langan and Horton, 2005). In this regard, chlorophyll-*a* concentration was used as an indicator of food availability to sustain the filter-feeding requirements for blue mussel grow-out. The temperature and chlorophyll-*a* thresholds that were used to locate areas with potential for favourable grow-out (Table 1) were obtained from reviews of the literature and through correspondence with researchers and aquaculture practitioners (Annex 1, Tables A1.1 to A1.4c).

Spatial data acquired through satellite remote sensing were indispensable for this study. The temperature and chlorophyll-*a* data used to identify areas with potential for good growth were taken from monthly archives. The archived data were used in two ways. The first way was to analyse the data to identify all of the areas meeting suitability thresholds; the second way was via parameter retrieval to estimate temperatures and chlorophyll-*a* concentrations at specific mariculture locations as part of the verification process. Annex 3 entitled "Remote sensing for the sustainable development of offshore mariculture" was paired with this technical paper in recognition of the importance of remote sensing to mariculture. This importance is not only as a source of data for spatial analyses to assess potential as was the use herein, but also for spatial analysis for zoning and siting, as well as for operational remote sensing to aid mariculture management. The close relationship between spatial analysis for aquaculture and remote sensing of environmental variables is also described by Dean and Popolus (2013).

Identifying competing, conflicting and complementary uses of ocean space

At first glance it may appear that the space for the development of offshore mariculture is limitless. However, especially near to shore, there are many possible competing, conflicting or complementary uses of ocean space. Many such areas are defined locally, and to deal with them individually is beyond the scope of this technical paper. Nevertheless, a possible competing offshore use is marine protected areas (MPAs). MPAs were selected because the database is global and because MPAs can be both national and international in scope. The other use criterion was illustrated by estimating the area that would be lost by hypothetically excluding open ocean mariculture of cobia in MPAs, with MPAs defined by the International Union for Conservation of Nature (IUCN) and the United Nations Environment Programme-World Conservation Monitoring Centre (UNEP-WCMC) (2010).

1.2.3 Comparisons of predicted offshore potential with inshore mariculture practice and verifications at offshore mariculture sites

Ideally, results are verified; however, verification was difficult because the predictions of offshore mariculture potential are for an industry that largely does not yet exist. Nevertheless, the predictions of potential were tested by making three kinds of comparisons based on the offshore potential found for each of the three species-culture system combinations. The comparisons were:

(i) **Potential compared with production:** These were comparisons of offshore mariculture potential in square kilometres with the mariculture production of nations actually practising mariculture of that species-culture system combination at the national level. The rationale for a positive result from this comparison is simply that where mariculture already exists there is an advantage to its further development. Mariculture already in practice in a nation with the species used in this technical paper is indicative of established infrastructure, goods, services, juvenile production and other technologies, as well as access to markets to support offshore development.

(ii) **Offshore mariculture potential compared with inshore mariculture locations:** These were comparisons on maps at the national to local level of areas found to have offshore potential compared with the actual locations of inshore mariculture installations of those species, or with inshore farming areas in which mariculture of those species was being practised. The rationale for an advantage in the development of offshore mariculture in the areas where there is a correspondence between offshore potential and inshore practice is the same as for the national- level comparison above, but with the advantage of inshore practice being proximate to offshore areas with potential for development.

(iii) **Offshore mariculture potential compared with actual offshore mariculture locations:** These were comparisons on maps of local areas with offshore mariculture potential with the actual locations of offshore installations. These comparisons are the actual verification of the results.

1.2.4 Basic requirements and constraints on the study

The basic requirements of this study were that the results had to be comprehensive of all maritime nations whether or not they were practising mariculture and that they had to be comparable among them. The estimates of offshore potential were to be expressed separately for mariculture-practicing nations and those nations yet to develop mariculture in two ways: aggregated globally and at the national level. The summary tables of the results of the spatial analyses presented in Olsen *et al.* (forthcoming) express the results in terms of potential in relation to climate zones. However, for this technical paper, while climate zones are retained as layers in the map figures as a link to the earlier results, the focus is on offshore mariculture potential by sovereign nation with the results ranked and reported for the top 20 among mariculture nations and non-mariculture nations alike. The terms “mariculture nations” and “non-mariculture nations” are a concise way of designating nations that already practise mariculture and those nations not yet practising mariculture. The boundaries of sovereign nations were taken from the GADM database of Global Administrative Areas (2009) described in Annex 1, Table A1.1.

One of the self-imposed constraints on this technical paper was that all of the data had to be freely downloadable from the Internet so that, ideally, anyone could repeat or expand the analyses herein. These data sets are described in Annex 1, Table A1.1. Also, many of the key spatial data sets derived from the original sources for this study can be downloaded from the FAO Geonetwork (www.fao.org/geonetwork/srv/en/main.home).

Another constraint was that all of the spatial analyses had to be accomplished on desktop computers using readily available geographic information system (GIS) software to allow for replication or expansion. This constraint was met except for the current speed analyses. It was necessary to have the original current data sub-sampled and extracted from the HYbrid Coordinate Ocean Model (or HYCOM) current speed model (Annex 1, Table A1.1) before they could be transferred to the desktop computer workstations for final analyses. Manifold (CDA International Ltd.) and ArcGIS 9.3 (ESRI – Environmental Systems Research Institute) were the GIS software used, the latter for the more complex, repetitive and time-consuming analyses that were conducted using custom Visual Basic for Applications (VBA) functions within ArcGIS 9.3, culminating as shapefiles[4] that were then analysed in Manifold. Results of spatial analyses were exported to Microsoft Excel 2010 in which they were reported using pivot tables and pivot charts. Offshore mariculture potential was reported as maps showing the areas with potential, tables that presented surface areas in aggregate globally, and charts with potential ranked by the main nations, usually 20 in number, meeting various criteria.

[4] A shapefile is a digital vector storage format for storing geometric location and associated attribute information.

2. Status of mariculture from a spatial perspective

The objective of this chapter is to portray the current status of mariculture spatially in terms of the intensity of existing inshore mariculture production. The rationale and approach are similar to those set out in more detail by Kapetsky, Aguilar-Manjarrez, and Soto (2010 pp. 75–88).

The data sets used in this chapter, the mean annual mariculture production by weight and by country from 2004 to 2008 (FAO Statistics and Information Branch of the Fisheries and Aquaculture Department, 2010) and the coastline length by country established by GIS analyses, are described in Annex 1, Table A1.1. The latter data set was generated especially for this study and the methods are described in Annex 1.

2.1 Nominal intensity of the use of the coastline for mariculture at the national level

Mariculture is widespread geographically throughout all climate zones except in Antarctica. In all, 93 countries and territories practised mariculture during the period 2004–2008, and there were 72 maritime countries and territories that were not yet practising it. As mentioned previously, most mariculture production comes from protected inshore waters at or near the coastline (i.e. waters sheltered by headlands, islands, sandbanks, reefs and other physical features). At the national level, coastline length is basic to mariculture potential because it is a measure of "frontage for development". It is from the coastline that offshore mariculture will be supported and from which development will proceed seaward. Mariculture nations possess about 1.47 million km of coastline whereas non-mariculture nations have only about 0.3 million km (Table 2). An important point is that for offshore mariculture the requirement of shelter is removed. Thus, all coastal frontage theoretically becomes available for offshore mariculture, unlike current inshore mariculture that tends to be constrained by the availability of sheltered waters.

TABLE 2

Status of mariculture from a spatial perspective

Criteria	Mariculture nations		Non-mariculture nations		Total	
Production	Countries and territories*	Mean production (tonnes) 2004–08	Countries and territories	Mean production (tonnes) 2004–08	Countries and territories	
	93	29 976 736	72	0	165	
Coastline length	Nations	km	Nations	km	Nations	km
	80	1 472 111	83	302 548	163	1 774 659

Mariculture intensity of 93 countries and territories	Production of aquatic plants and animals (tonnes/km coastline)
Mean (tonnes/km)	15
Median (tonnes/km)	1
Maximum (tonnes/km)	519

*Databases for production by countries and territories and for coastline length differ slightly in numbers of countries and territories. The FAO statistical database contains production attributes assigned to country and territory names. It reports production from some territories separately from their associated sovereign nations. In contrast, coastline length was derived for this study using GIS methods from a different set of country and territory associations in digital format in which each coastline is a spatial object from which its length becomes an attribute. The differences have been taken into account in estimating mariculture intensity.

Whereas coastline length is a very basic measure of mariculture potential in terms of frontage for development, so is intensity of total mariculture production expressed as tonnes/km of coastline by nation, a baseline measure of actual use of the coastline for mariculture. This is only a crude measure of mariculture intensity because coastal farms are not homogeneously distributed along the sea coast. But because of the non-homogeneous distribution of mariculture, it does express minimum use of the coastline for that purpose, however crude. Mariculture, including fish, invertebrates and aquatic plants, is diverse in terms of the intensity of its practice, covering five orders of magnitude, with ranges from a fraction of a tonne/km in many countries up to 519 tonnes/km in the People's Republic of China where seaweed is a significant part of mariculture (Figure 4). After considering the People's Republic of China, the intensity of mariculture production drops to less than 100 tonnes/km of coastline (Figure 5).

FIGURE 4
Intensity of mariculture production (2004–2008) in tonnes per kilometre of coastline and numbers of countries in the range

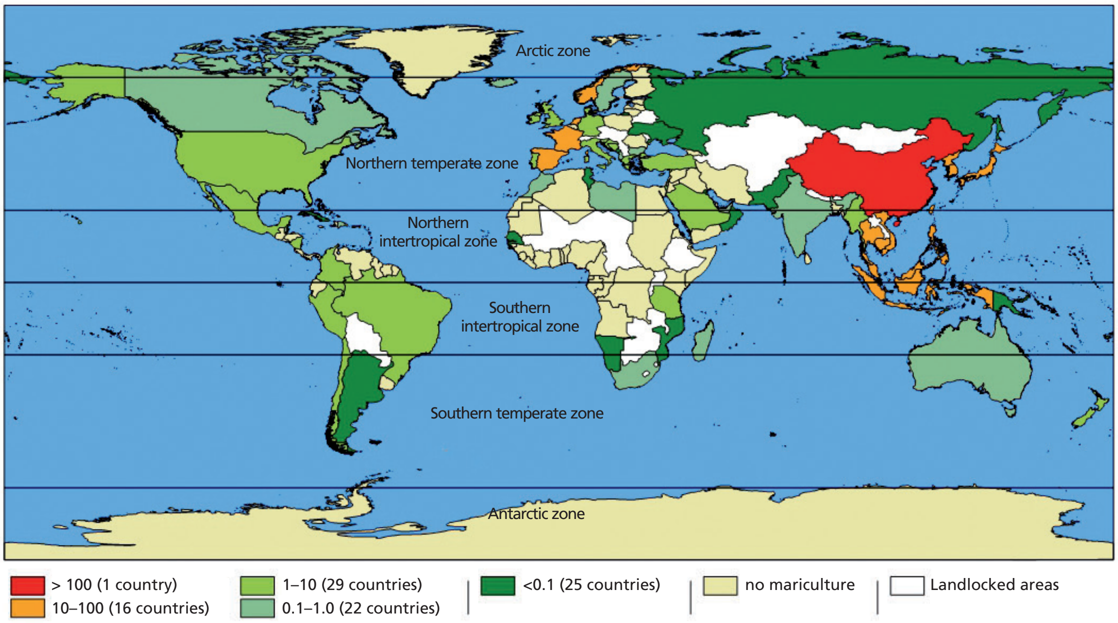
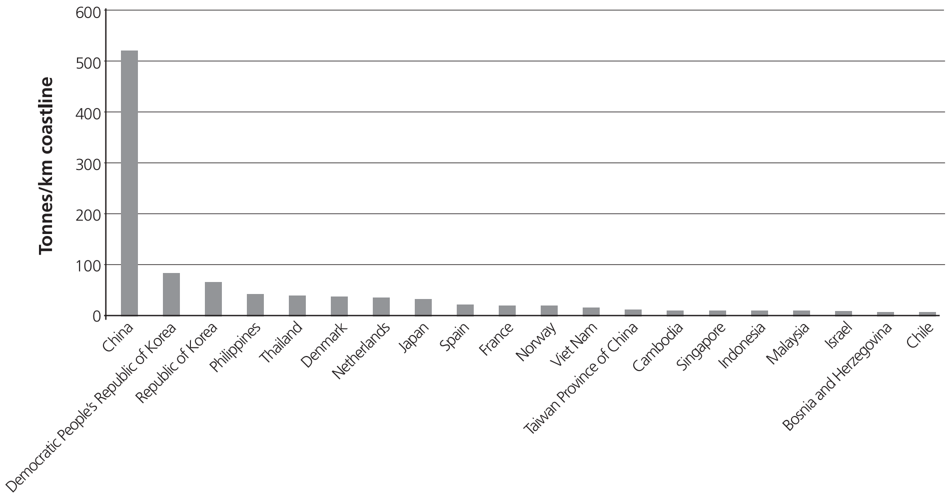


FIGURE 5
Ranking by area of main nations in intensity of mariculture (tonnes/km coastline) production (2004–2008)



In summary, the present status of mariculture suggests that the global potential for offshore mariculture in aggregate and for many nations individually is large for the following reasons:

(i) Forty-four percent of maritime nations are not yet practising mariculture.

(ii) There are 0.3 million km of coastline where mariculture is not yet practised.

(iii) Among the 93 countries and territories already practising mariculture, one-half produce at a relatively low intensity of less than 1 tonne/km of coastline.

(iv) It is well known that nearly all of present-day mariculture takes place in sheltered inshore waters and not in offshore waters (Plates 4 and 5).

PLATE 4
Net cages along the coast of Turkey

COURTESY OF OF O. ALTAN

PLATE 5
Net cages along the coast of Norway

COURTESY OF Y. OLSEN

3. Exclusive economic zones as spatial frameworks for offshore mariculture development

Spatially defined reference frameworks are necessary for a common understanding of where and at what pace offshore mariculture can develop both within and among countries. Mariculture can develop from the coastline to well offshore, but, initially, it is unlikely to develop outside of the protection afforded by the legal jurisdictions of each maritime nation that has declared an EEZ. For these reasons, EEZs serve as the baseline areas within which offshore mariculture is assessed in this study. EEZs extend from a coastal baseline up to 200 nm (370.4 km) offshore and are subdivided into various kinds of maritime claims. The actual shapes and area expanses of EEZs are determined by the United Nations Convention on the Law of the Sea. At present, some countries have not declared an EEZ, and in the future free-floating or propelled mariculture structures may be developed for use on the high seas and they may pass from one EEZ to another. These cases will require special legal frameworks for international mariculture development.

The total EEZ area of nations already practising mariculture amounts to about 131 million km^2 and 33 million km^2 for non-mariculture nations (Figure 6). Among the mariculture nations with the largest EEZ area are the French Republic, the United States of America, and the Kingdom of Denmark when overseas territories are included (Figure 7). This underlines an important point: the land area of the homeland of a sovereign nation does not necessarily equate to its total EEZ area. In the case of the French Republic and the Kingdom of Denmark, it is their overseas territories that

FIGURE 6
Economic zones as spatial frameworks for offshore mariculture development

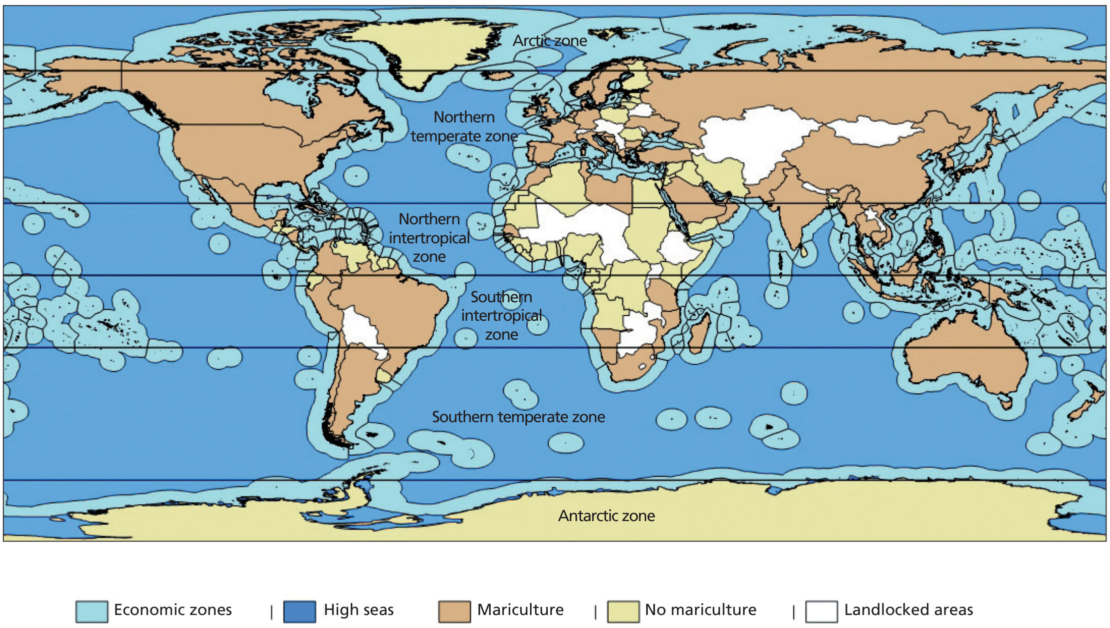


FIGURE 7
Ranking by area of main mariculture nations in area of economic zones

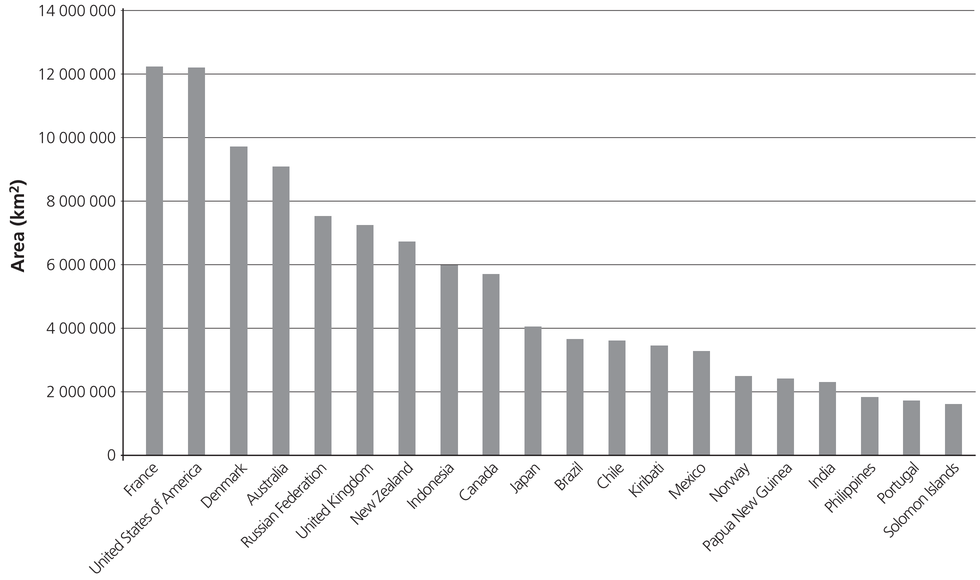
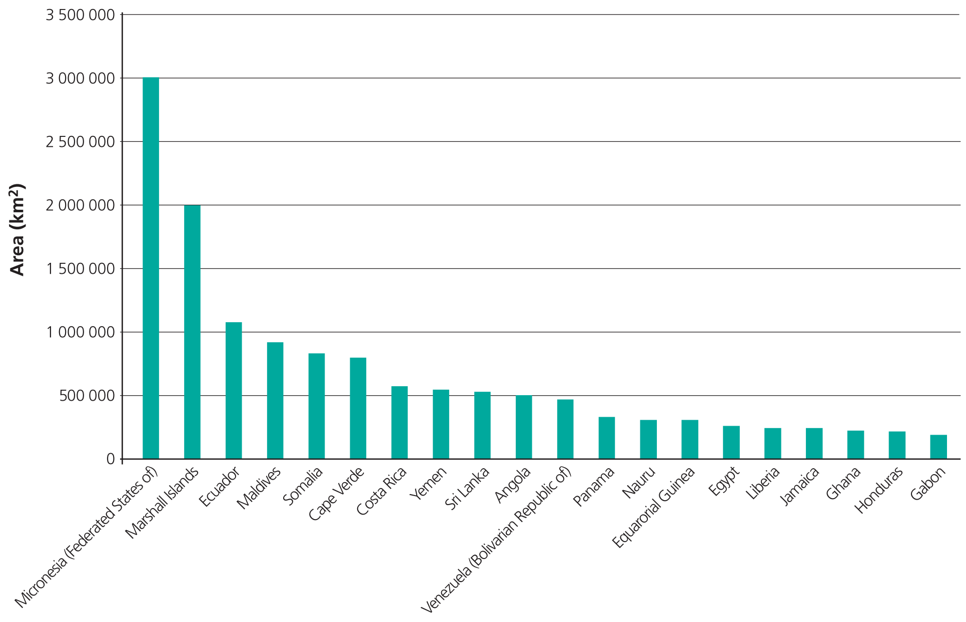


FIGURE 8
Ranking by area of main non-mariculture nations in area of economic zones



contribute greatly to the total EEZ area of these sovereign nations. The same point emerges in considering the EEZ area of non-mariculture nations in which those with the largest EEZ areas – the Federated States of Micronesia and the Republic of the Marshall Islands – possess relatively small land areas (Figure 8). Antarctica figures as having a large EEZ because the Flanders Marine Institute, the makers of the EEZ digital map (Annex 1, Table A1.1), did not recognize national EEZ claims on the continent. Because there is no mariculture in Antarctica and nor is there likely to be any development there in the near future, this does not detract from this study and for this reason Antarctica is not further treated in this study.

4. Potential for offshore mariculture development

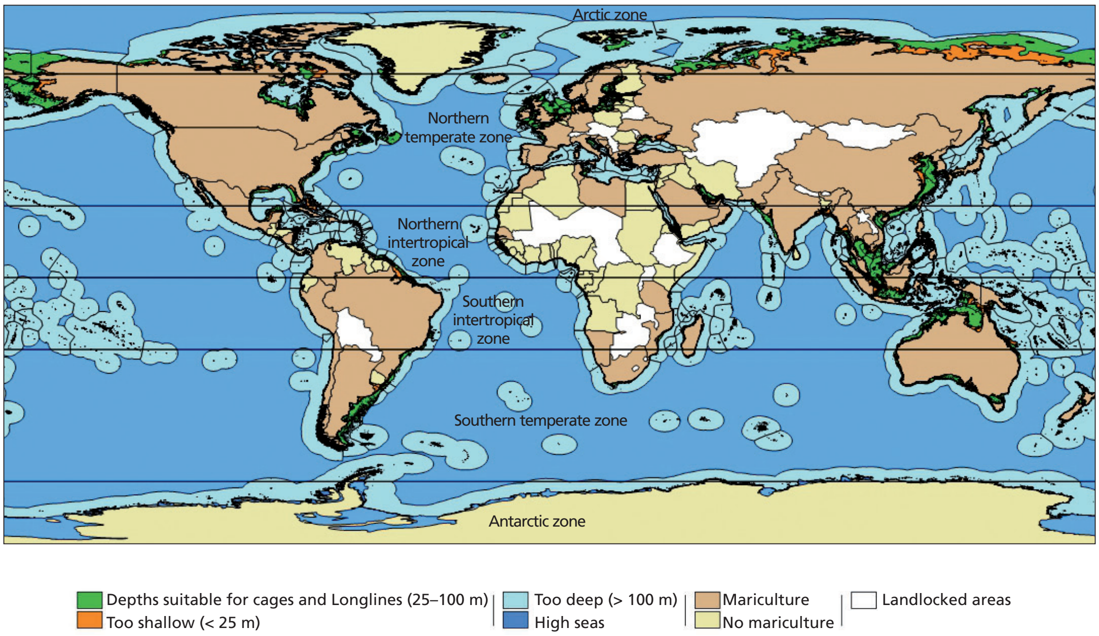
4.1 Overview

This chapter sets out offshore mariculture potential in a stepwise fashion. First, environments where it is technically feasible to place offshore cages for fish and longlines for mussels are established on the basis of water depth and current speed. The cost-effective area for development, one of many measures of economic feasibility of offshore mariculture within EEZs, is established in terms of access to a port and as the area that lies within 25 nm (46.3 km) of a port. Second, environments for favourable grow-out of cultured organisms are identified based on temperature for all three species and on chlorophyll-*a* concentration for the mussel. Then, environments for favourable grow-out are spatially integrated with the locations suitable for cage and longline systems as well as with cost-effective areas for offshore development. Finally, MPAs, as examples of locations that can compete or conflict with offshore mariculture for ocean space, are identified with respect to potential for offshore cobia culture.

4.2 Areas where it is technically feasible to place culture installations

The first technical measure of potential was depths suitable for submerged cages for fish and submerged longlines for shellfish (25–100 m) (Figure 9). Total global potential in this regard amounts to 12.4 million km^2 among the 82 mariculture nations, but only 1.0 million km^2 among the 71 non-mariculture nations (Table 3). Among the mariculture nations with the largest areas suitable for cages and longlines in this depth range are the Russian Federation, Australia and the Republic of Indonesia (Figure 10). For the Russian Federation, much of the area meeting the depth criterion is at high latitudes and

FIGURE 9
Areas with depths suitable for sea cages and longlines within economic zones



may not be available because of ice cover. Among the non-mariculture nations with the largest areas suitable for cages and longlines in this depth range are the Islamic Republic of Iran, the Bolivarian Republic of Venezuela and the Republic of Finland (Figure 11).

TABLE 3
Number of nations and corresponding areas meeting depth, current speed and cost-effective area criteria for offshore mariculture development

Technical and economic feasibility	Mariculture nations		Non-mariculture nations		Total	
	Nations	Area (km²)	Nations	Area (km²)	Nations	Area (km²)
Depths suitable for cages and longlines (25–100 m)	82	12 405 003	71	1 000 446	153	13 405 449
Current speed suitable for cages (10–100 cm/s)	77	84 244 659	69	16 790 002	146	101 034 662
Depths (25–100 m) and current speeds (10–100 cm/s) suitable for cages and longlines	73	1 234 771	65	190 383	138	1 425 154
Cost-effective area (25 nm, or 46.3 km, from a port)	79	5 119 018	74	1 015 430	153	6 134 448
Cost-effective area (25 nm, or 46.3 km, from a port) and depths and current speeds suitable for cages	69	146 820	52	42 648	121	189 468

FIGURE 10
Ranking by area of main mariculture nations in depths suitable for sea cages and longlines

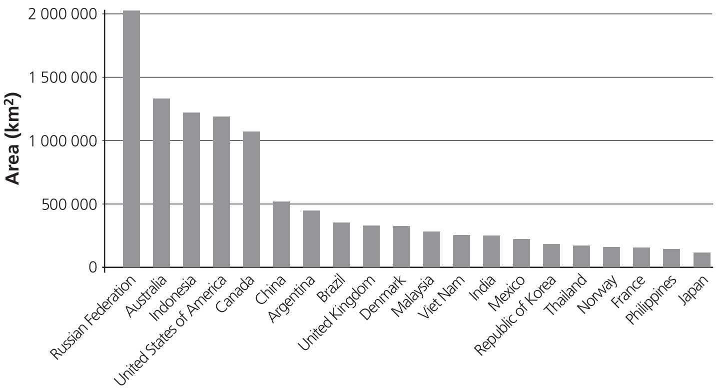
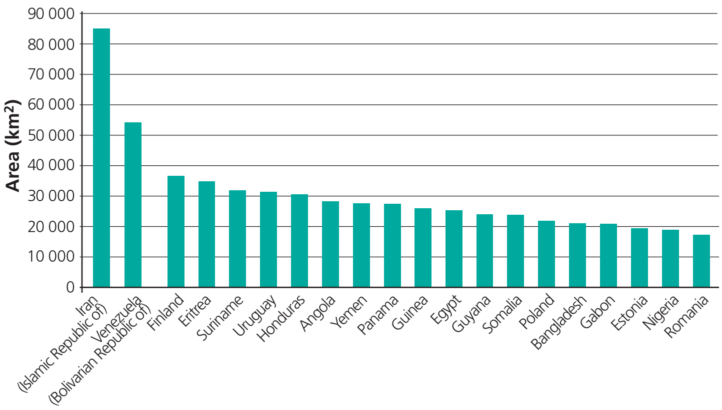
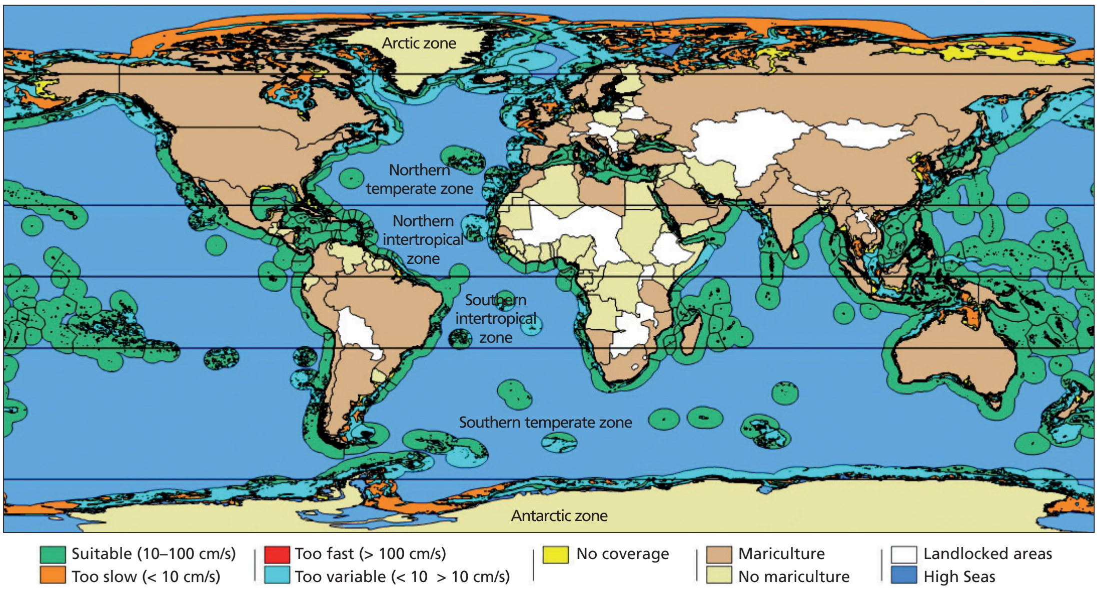


FIGURE 11
Ranking by area of main non-mariculture nations in depths suitable for sea cages and longlines



The second measure of technical potential was current speeds suitable for sea cages and longlines. The importance of current speeds as a fundamental criterion for assessing potential cannot be overemphasized for its effects on the endurance of culture structures and on the well-being of cultured organisms (Figure 2). Globally, there are large areas totalling 84.2 million km² within EEZs that have current speeds within the 10–100 cm/s threshold range. There are 77 mariculture nations, and 16.8 million km² among the 69 non-mariculture nations meeting this criterion (Table 3; Figure 12). Leading nations among those already practising mariculture are the French Republic, the United States of America and Australia (Figure 13). Leading non-mariculture nations with current speeds suitable for cages and longlines are the Federated States of Micronesia, the Republic of the Marshall Islands and the Republic of Ecuador (Figure 14).

FIGURE 12
Areas within EEZs with current speeds suitable for sea cages and longlines



Note: Areas that were identified as too fast (> 100 cm/s) are not visible at a global scale.

As would be expected with the integration of the thresholds of two technical criteria (water depths suitable for cages and longlines and current speeds), the area fulfilling both criteria is much reduced. Among the 73 mariculture nations, it is 1.2 million km^2 and among the 65 non-mariculture nations, it is only 190 000 km^2 (Table 3). The Federative Republic of Brazil, (Figure 15)[5], the Republic of Indonesia and the United States of America possess the largest area that is suitable depth-wise and in current speed for cages and longlines (Figure 16). Among the non-mariculture nations, the Bolivarian Republic of Venezuela, the Somali Republic and the Republic of Uruguay are the most important in this regard (Figure 17).

FIGURE 13
Ranking by area of main mariculture nations with current speeds suitable for sea cages and longlines

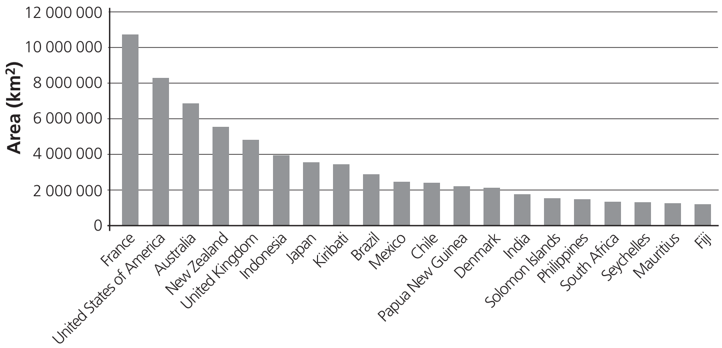
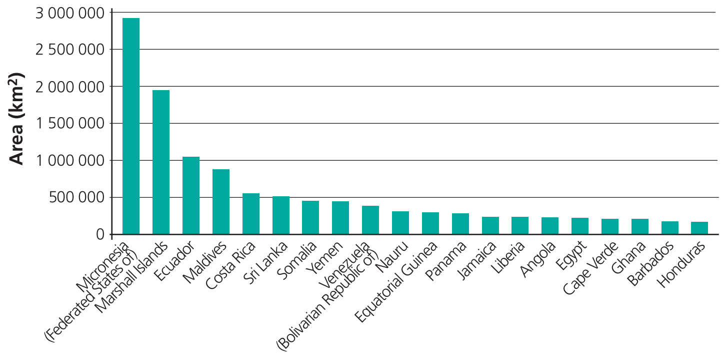


FIGURE 14
Ranking by area of main non-mariculture nations with current speeds suitable for sea cages and longlines



[5] Not all measures of offshore mariculture potential can be discerned on a map with a global view. Thus, regional views are used to call attention to countries with high potential.

FIGURE 15

Areas in northern Latin America with current speeds and depths suitable for sea cages and longlines

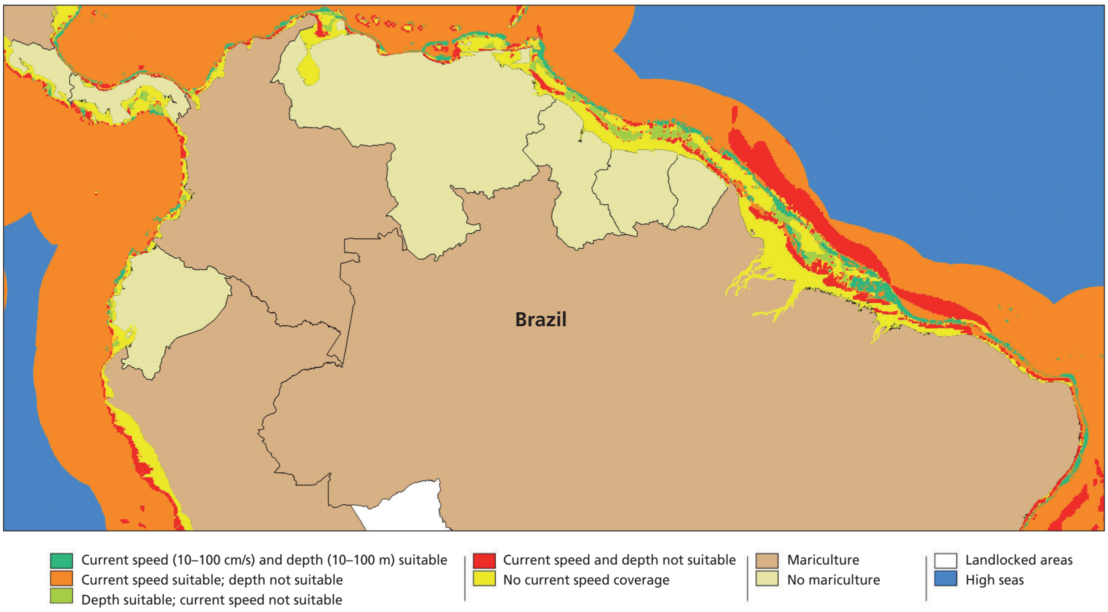


FIGURE 16

Ranking by area of main mariculture nations with current speeds and depths suitable for sea cages and longlines

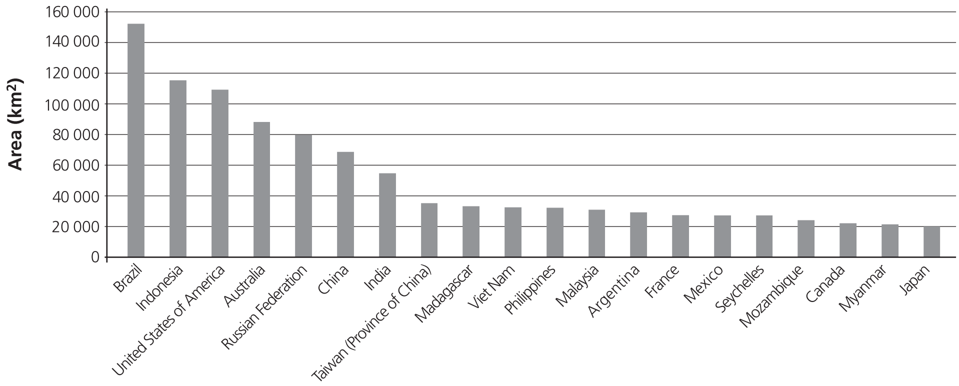
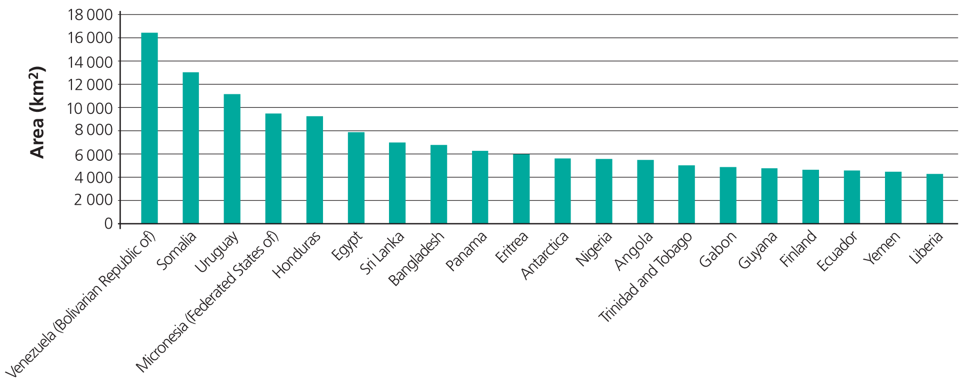


FIGURE 17

Ranking by area of main non-mariculture nations with current speeds and depths suitable for sea cages and longlines



4.2.1 Areas within a cost-effective distance for offshore mariculture development and with access to ports

The economic feasibility of offshore mariculture is a broad topic that involves the analysis of many variables. As with offshore mariculture itself, the economics of offshore mariculture is in its infancy and there are only a handful of studies cited by Knapp (forthcoming) that relate this topic. Nevertheless, one important spatial aspect of economic feasibility was analysed in this study: the cost-effective area for development. It consists of two components. The first is the cost-effective distance from the coastline to an offshore installation - 25 nm (46.3) - adopted from Jin (2008). The second component refers to the locations suitable for onshore support facilities with all-weather access to the sea. This component was spatially represented by the locations of world ports (World Port Index, 2009). Integration of the two components defines the cost-effective area for development that is the sea area that is within a 25 nm radius from a port. The total cost-effective area for development is 5.1 million km^2 among 79 mariculture nations and 1.0 million km^2 among 74 non-mariculture nations (Table 3; Figure 18). Among the mariculture nations, the United States of America, the Republic of Indonesia and Canada are the most prominent (Figure 19). The non-mariculture nations with the greatest cost-effective area for development are the Republic of Angola, the Republic of Finland and the Islamic Republic of Iran (Figure 20).

FIGURE 18
Cost-effective area for offshore mariculture development that is within 25 nm of a port

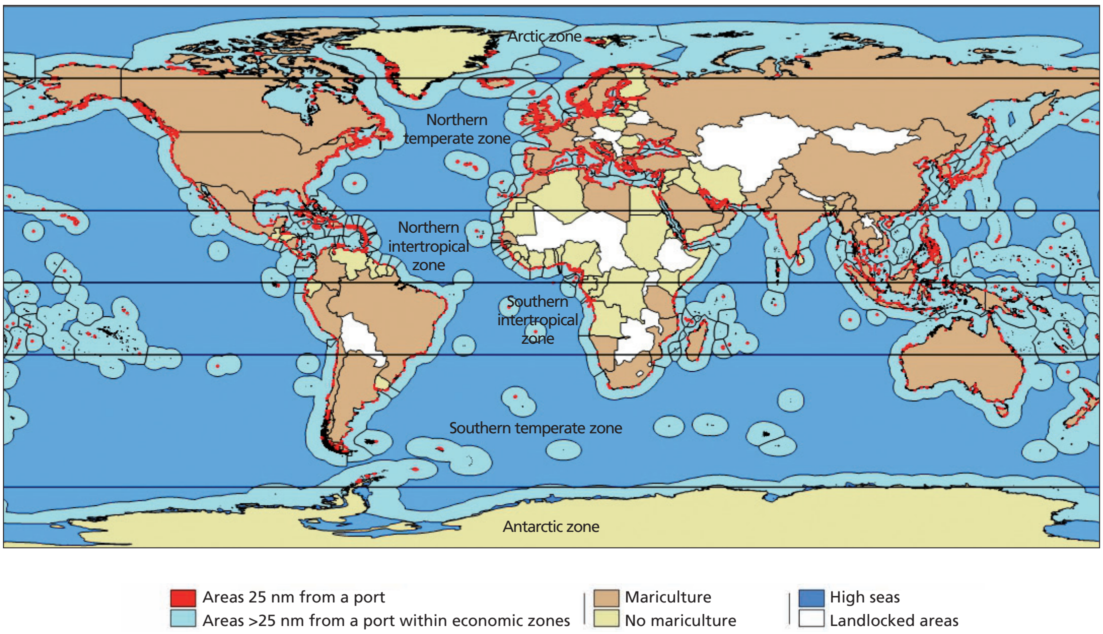


FIGURE 19
Ranking by area of main mariculture nations in cost-effective area for development

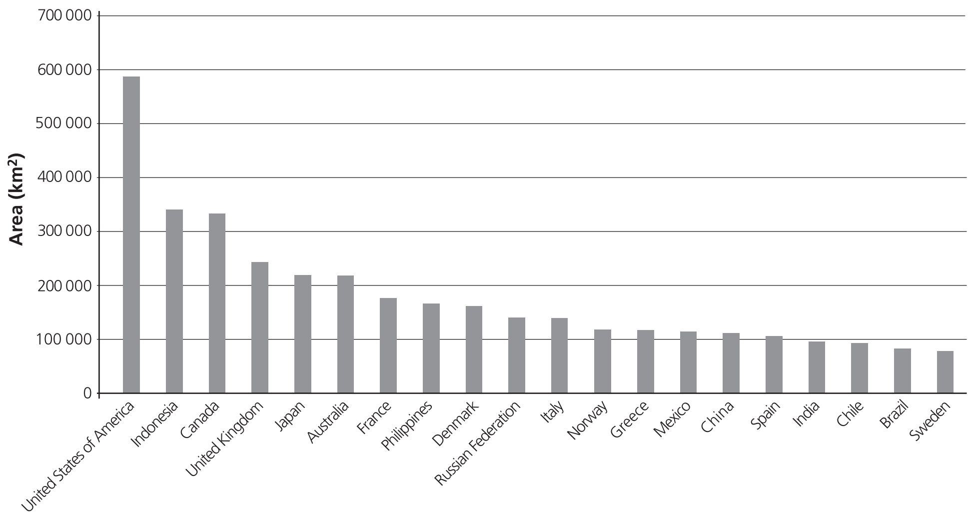
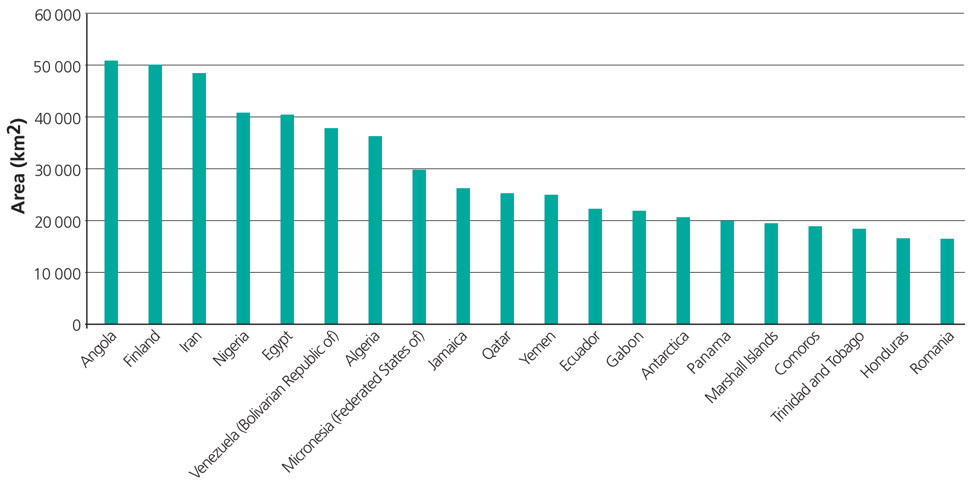


FIGURE 20
Ranking by area of main non-mariculture nations in cost-effective area for development



4.2.2 Spatial integration of technical feasibility for cages and longlines with cost-effective area for development

Spatial integration of water depth and current speed suitable for cages and longlines and cost-effective area for development resulted in relatively modest areas: 147 000 km^2 for mariculture nations and 43 000 km^2 for non-mariculture nations. However, the number of nations included is relatively high, 69 and 52 for mariculture and non-mariculture nations, respectively (Table 3). The mariculture nations with the largest areas meeting all three criteria are the Federative Republic of Brazil, the Republic of India and the Taiwan Province of China (Figure 21). The non-mariculture nations that lead in suitable area are the Federal Republic of Nigeria, the Bolivarian Republic of Venezuela and the Republic of Liberia (Figure 22).

FIGURE 21
Ranking by area of main mariculture nations with current speeds and depths suitable for sea cages and longlines and within the cost-effective area for development

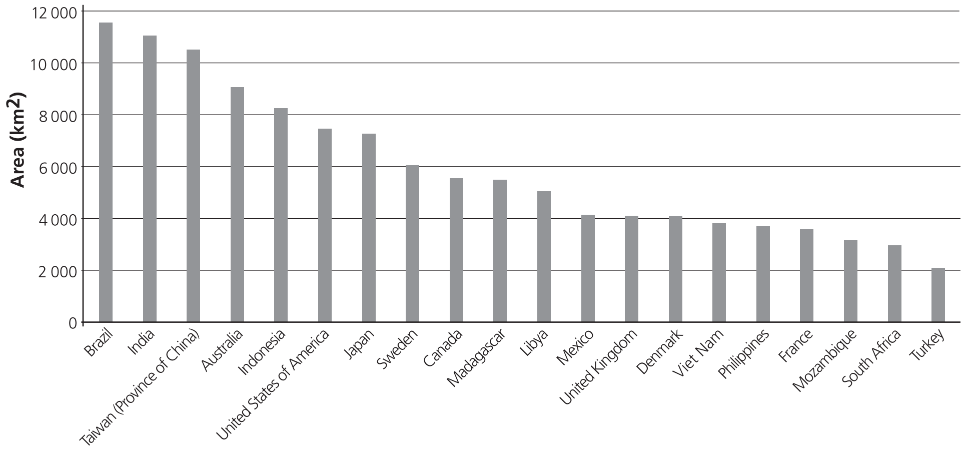
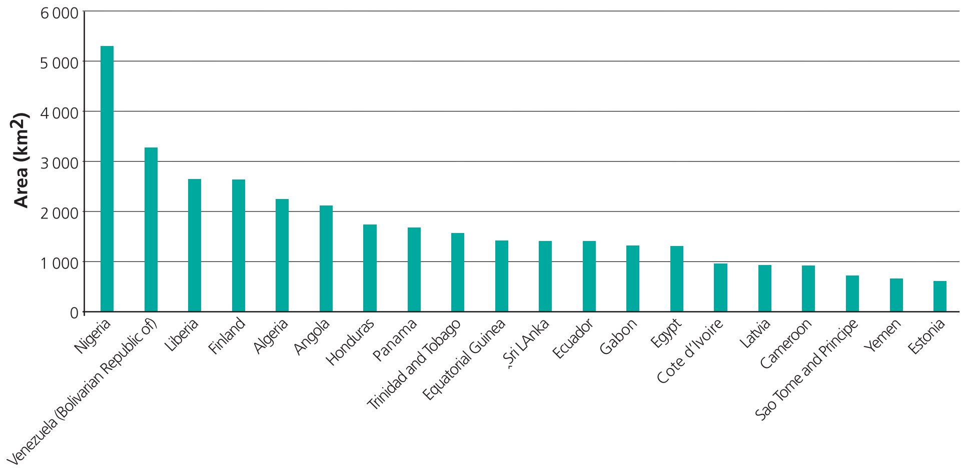


FIGURE 22
Ranking by area of main non-mariculture nations with current speeds and depths suitable for sea cages and longlines and within the cost-effective area for development



The results above (Figures 21 and 22) call attention to the nations that have the largest areas with potential when all three criteria are spatially integrated. Likewise, the results from Sections 4.2 and 4.3 show the results when the criteria are treated individually. However, it is of interest to identify the nations that have all-around potential. Those are the nations that have both high area-wise potential and that also consistently rank highly across all three of the criteria for offshore mariculture development potential. Those nations were identified by selecting those that ranked among the first 20 across all three criteria: depth for cages and longlines, current speeds for cages and longlines, and cost-effective area for economic development. Then the ranks achieved in each criterion were summed to make an overall score. The possible range of scores is from 3 (most potential) to 60 (least potential). Among the mariculture nations, there were 10 that appeared among the ranking top 20 with regard to all three criteria. Among those nations, the United States of America, the Republic of Indonesia and Australia scored highest. Similarly, for the non-mariculture nations five appeared among all of the criteria. Among those, the Bolivarian Republic of Venezuela, the Republic of Angola and the Republic of Yemen scored best (Table 4).

TABLE 4
Nations consistently scoring high in potential for offshore mariculture development in technical and cost-effective area for development as measured by ranks and overall scores

Nation	Cages and longlines				Cost-effective area		Overall score
	Depth suitable		Current speed suitable				
	Rank	Area (km^2)	Rank	Area (km^2)	Rank	Area (km^2)	
Mariculture nations							
United States of America	4	1 190 441	2	8 277 236	1	587 387	7
Indonesia	3	1 220 487	6	3 949 545	2	340 352	11
Australia	2	1 333 993	3	6 869 770	6	218 361	11
United Kingdom	9	330 699	5	4 821 415	4	242 888	18
France	18	155 302	1	10 720 729	7	177 013	26
Japan	20	118 197	7	3 553 548	5	218 753	32
Denmark	10	324 421	13	2 107 512	9	161 082	32
Brazil	8	353 479	9	2 865 618	19	83 096	36
Philippines	19	142 131	16	1 458 577	8	166 666	43
India	13	248 777	14	1 750 865	17	95 634	44
Non-mariculture nations							
Bolivarian Republic of Venezuela	2	54 355	9	383 994	6	37 859	17
Angola	8	28 289	15	231 565	1	50 916	24
Yemen	9	27 605	8	447 196	11	25 055	28
Egypt	12	25 373	16	219 927	5	40 473	33
Honduras	7	30 626	20	170 655	19	16 578	46

4.2.3 Summary of technical feasibility for cages and longlines and the cost-effective area for development

The following are the salient results from this section on the technical feasibility for cages and longlines and on the cost-effective area for the development of offshore mariculture.

(i) As a group, nations already practising mariculture possess much more area than nations yet to develop mariculture with regard to offshore area suitable for cages and longlines in terms of depth, current speed, integrated depth and current speed, cost-effective area for development, and with all of these criteria spatially integrated and when successively integrated (Figure 23). Nevertheless, the absolute areas with offshore potential are large collectively both for mariculture and non-mariculture nations alike, and the number of nations with offshore potential is large even where the area is relatively small (Figure 24).

(ii) Nations that are the current leaders in inshore mariculture production (e.g. the top three in the period 2004–2008 – the People's Republic of China, the Republic of the Philippines, Japan) – are not necessarily those with the greatest offshore areas suitable for cages and longlines and within the cost-effective area for development (e.g. Figure 21).

(iii) Ten mariculture nations and five non-mariculture nations with consistent relatively large potential for offshore mariculture development across all technical and economic criteria have been identified (Table 4).

(iv) These results, in addition to those set out in Chapter 2, point to much unrealized offshore mariculture potential from global and from national viewpoints alike.

FIGURE 23
Offshore mariculture potential for sea cages and longlines by areas meeting depth, current speed and cost-effective area for development criteria

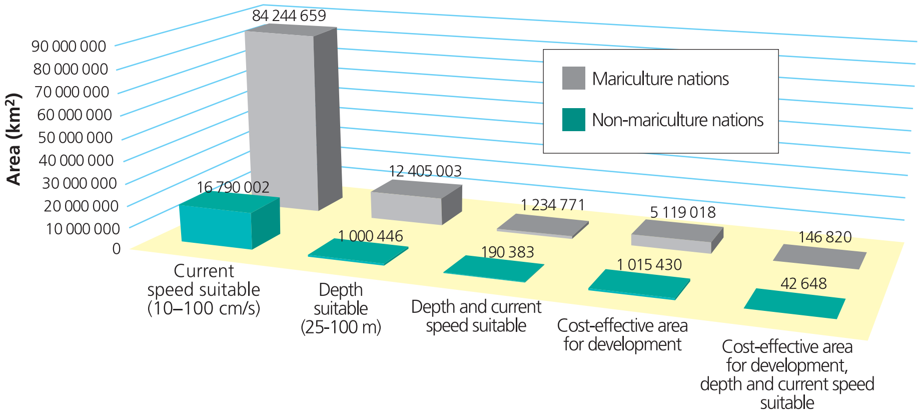
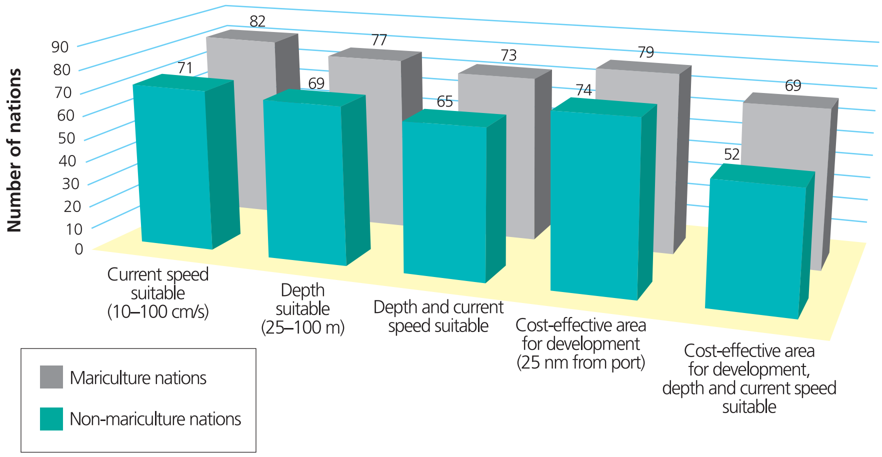


FIGURE 24
Offshore mariculture potential for sea cages and longlines by numbers of nations meeting depth, current speed and cost-effective area for development criteria



4.3 Areas favouring grow-out of fish and mussels spatially integrated with areas technically feasible for cages and longlines

In this section, temperature is introduced as an environmental variable defining the space suitable for the favourable grow-out of three species: cobia, Atlantic salmon and blue mussel. For the last species, a filter feeder, the concentration of chlorophyll-*a* also is used to identify areas with favourable grow-out potential. Additionally, areas for IMTA (Soto, 2009) of the Atlantic salmon and blue mussel are located based on the integration of the temperature thresholds favouring their grow-out and in meeting the chlorophyll-*a* concentration threshold for the blue mussel. Finally, the technical limits from the previous section, depths and current speeds suitable for culture installations, are integrated with the temperature and chlorophyll-*a* thresholds for these selected species in order to provide a broad picture of mariculture potential in species-culture system combinations as summarized in Table 5.

TABLE 5
Number of nations and corresponding areas with potential for favourable growth for cobia, Atlantic salmon and blue mussel integrated with suitable depth and current speed for cages and longlines

Growth and technical criteria	Mariculture nations		Non-mariculture nations		Total	
	Nations	Area (km^2)	Nations	Area (km^2)	Nations	Area (km^2)
Cobia temperature range 22–32 °C; depths and current speeds suitable for cages	44	658 031	40	135 907	84	793 938
Atlantic salmon temperature range 1.5–16 °C; depths and current speeds suitable for cages	14	30 566	0	0	14	30 566
Blue mussel temperature range 2.5–19 °C and chlorophyll-*a* > 0.5 mg/m^3; depths and current speeds suitable for longlines	15	29 960	0	0	15	29 960
IMTA temperature range 2.5 to 16 °C and chlorophyll-*a* > 0.5 mg/m^3; depths and current speeds suitable for cages and longlines	9	14 590	0	0	9	14 590

4.3.1 Areas favouring grow-out of fish and mussels

Areas with temperatures favouring grow-out of cobia (22–32 °C) within EEZs were identified (Figure 25). The areas with temperatures favouring cobia grow-out are vast and span the globe in much of the Intertropical Convergence Zone and in the small portions of the Northern and Southern Temperate Zones. The potential of cobia for offshore mariculture development was assessed by integrating the areas with favourable grow-out temperatures with depths and current speeds suitable for submerged cages.

FIGURE 25
Areas within EEZs with temperatures favourable for offshore grow-out of cobia

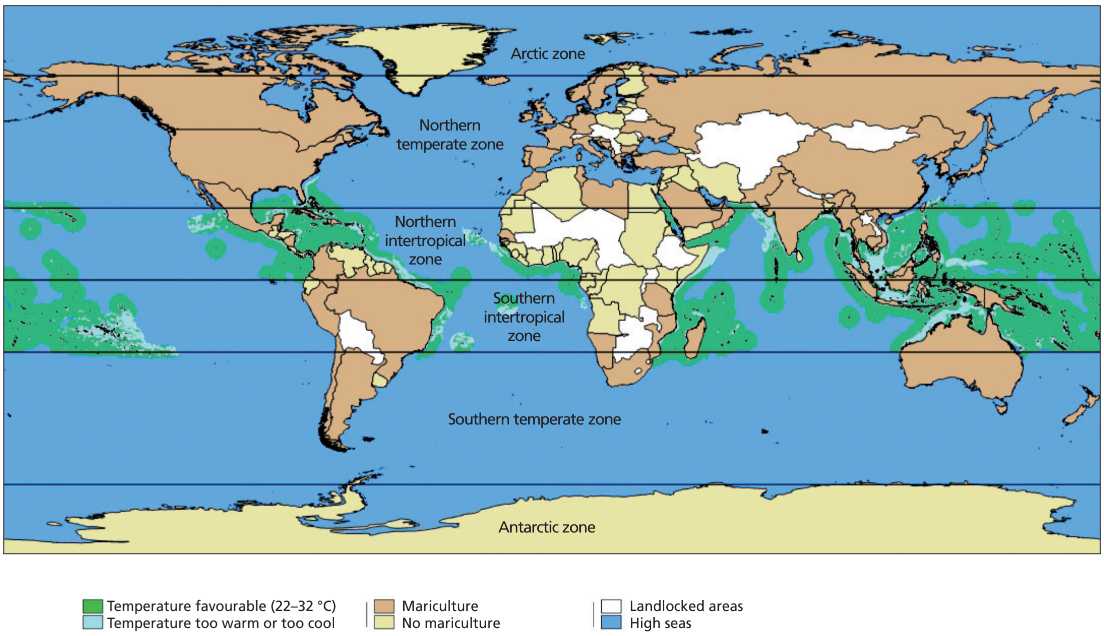
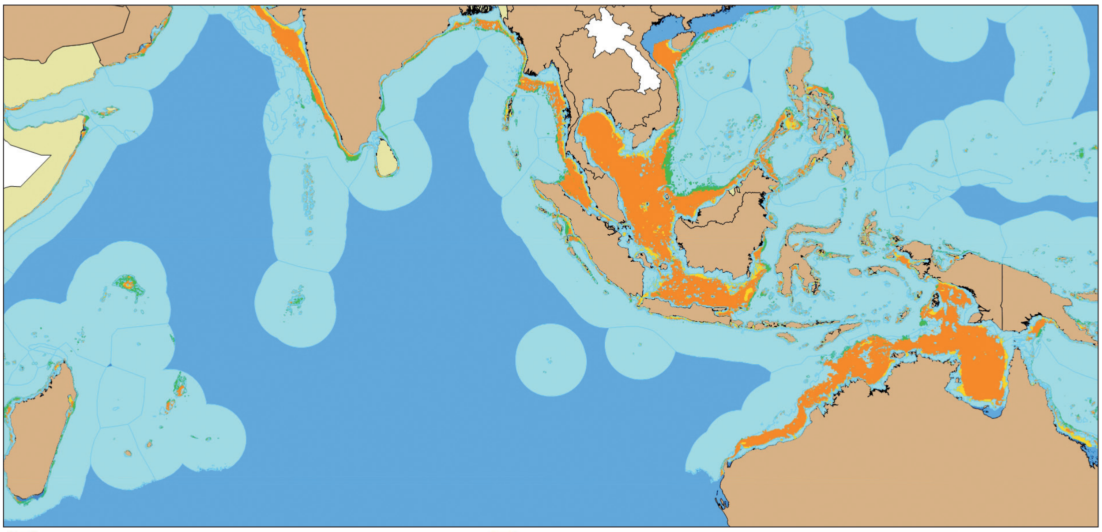


FIGURE 26
Regional view of areas in South Asia-Oceania with temperatures favourable for offshore grow-out of cobia and depths and current speeds suitable for sea cages



Temperature, depth and current speed suitable
Temperature and depth suitable, current speed not suitable
Mariculture
No mariculture
Temperature and depth suitable; no current speed coverage
Temperature suitable; depth and current speed not suitable in economic zone
Landlocked areas
High seas

Overall, potential for cobia amounts to 658 031 km^2 among 44 mariculture nations and 135 907 km^2 among 40 non-mariculture nations (Table 5). The mariculture nations with the largest potential are the Republic of Indonesia (Figure 26), the Federative Republic of Brazil and the Republic of India (Figure 27), and the leading non-mariculture nations are the Bolivarian Republic of Venezuela, the Somali Republic and the Federated States of Micronesia (Figure 28).

FIGURE 27
Ranking by area of main mariculture nations with temperatures favourable for cobia grow-out and current speeds and depths suitable for sea cages

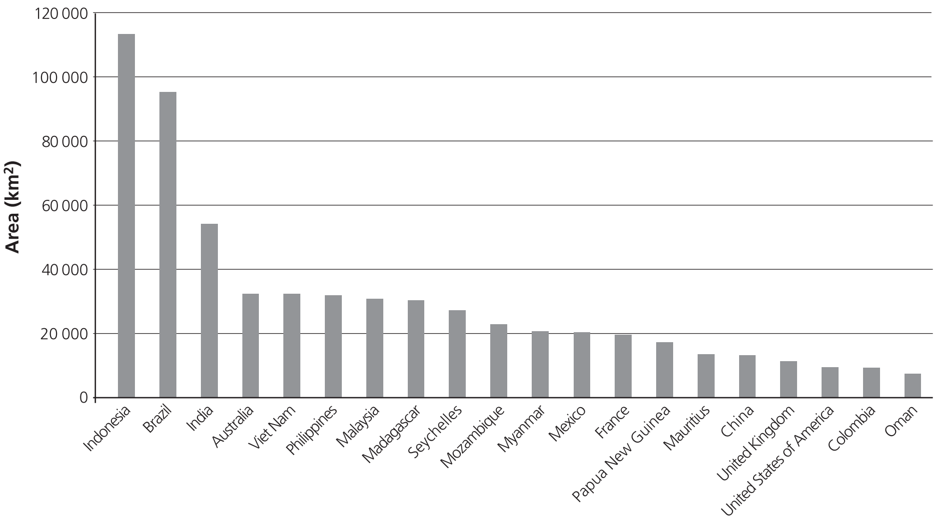
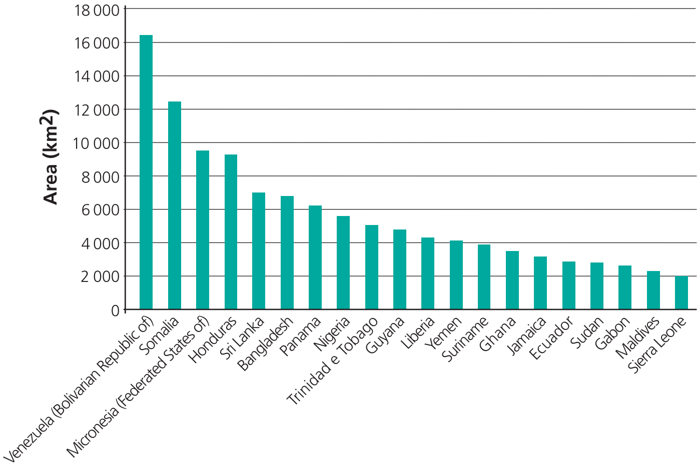


FIGURE 28

Ranking by area of main non-mariculture nations with temperatures favourable for cobia grow-out and current speeds and depths suitable for sea cages

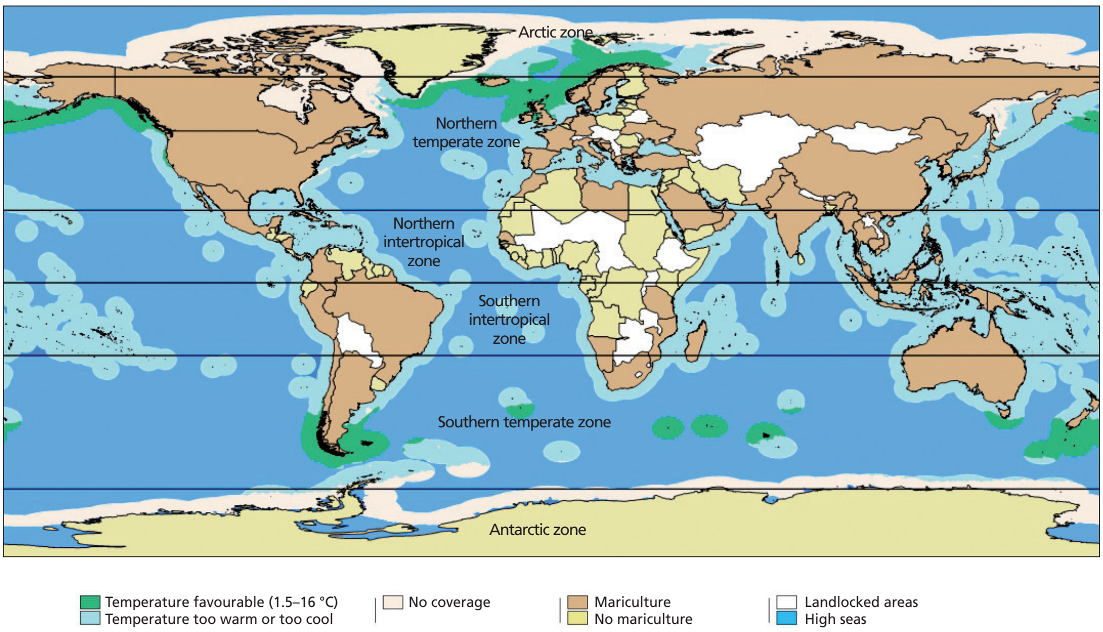


Potential for Atlantic salmon was identified by integrating its initial growth-temperature threshold (4–16 °C) with depths and current speeds suitable for cages. However, in the initial results, areas with existing inshore Atlantic salmon culture in the northeastern United States of America and southeastern Canada were not identified as having potential. Actual grow-out temperature data from the inshore culture sites of a major producer in this region were evaluated. The results indicated that salmon farming was successful at temperatures seasonally ranging as low as 1.5 °C. Accordingly, the lower threshold was extended to make a final threshold range of 1.5–16 °C. The global distribution of the temperatures favouring offshore Atlantic salmon grow-out within EEZs is shown in Figure 29. Areas where Atlantic salmon are already grown out in inshore waters are included, but there are other large areas with temperatures favouring offshore grow-out in the Northern and Southern Temperate Zones.

Global offshore potential for Atlantic salmon was found in a relatively modest area (31 000 km^2) among 11 mariculture nations, which includes three national territories as well (Table 5). The leading nations in Atlantic salmon potential are the Republic of Chile, the Argentine Republic and the French Republic, the last one by virtue of Southern Hemisphere territories. The United Kingdom of Great Britain and Northern Ireland also

FIGURE 29

Areas within EEZs with temperatures favourable for offshore grow-out of Atlantic salmon



has territories in the Southern Hemisphere that contribute to the overall area (Figure 30). There was no potential for Atlantic salmon among non-mariculture nations.

Potential for blue mussel mariculture in offshore waters was initially based on the integration of temperatures from 4 to 18 °C, a coastal chlorophyll-*a* concentration greater than 1 mg/m^3, and current speeds and depths suitable for submerged longlines (Section 4.2). These temperature and chlorophyll-*a* thresholds did not include the locations of some existing blue mussel culture areas in some countries in Europe and several offshore installations in the United States of America. Temperature and chlorophyll-*a* estimates from the spatial data archive along with actual in-water measurements from selected culture sites as well as temperature and chlorophyll-*a* concentrations obtained by parameter retrieval were examined and new thresholds were established at 2.5–19 °C and chlorophyll-*a* concentrations at > 0.5 mg/m^3. The global distribution of the areas meeting the temperature and chlorophyll-*a* thresholds within EEZs is shown in Figure 31. Large areas in the Northern and Southern Temperate Zones meet these thresholds. With the modified thresholds established and integrated with depths and current speeds for longlines, potential for offshore mariculture of blue mussel was found among 15 mariculture nations and territories in a total of 29 960 km^2. Among the mariculture nations, the Argentine Republic dominated followed by the Republic of Chile and Australia (Figure 32). No potential for offshore mariculture of the blue mussel was found among non-mariculture nations.

FIGURE 30
Ranking by area of main mariculture nations with temperatures favourable for Atlantic salmon grow-out and current speeds and depths suitable for sea cages

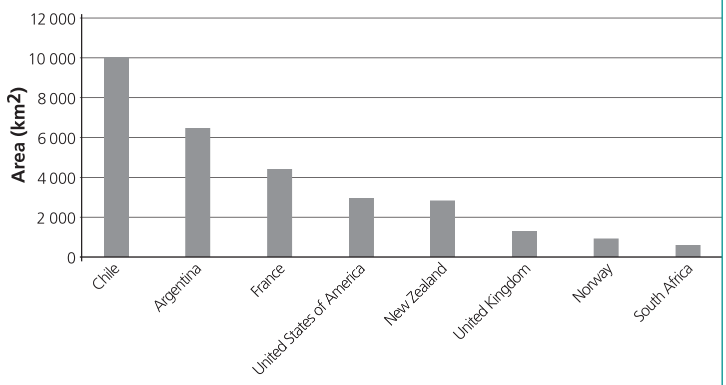


FIGURE 31
Areas within EEZs with temperatures and chlorophyll-*a* concentrations favourable for offshore grow-out of the blue mussel

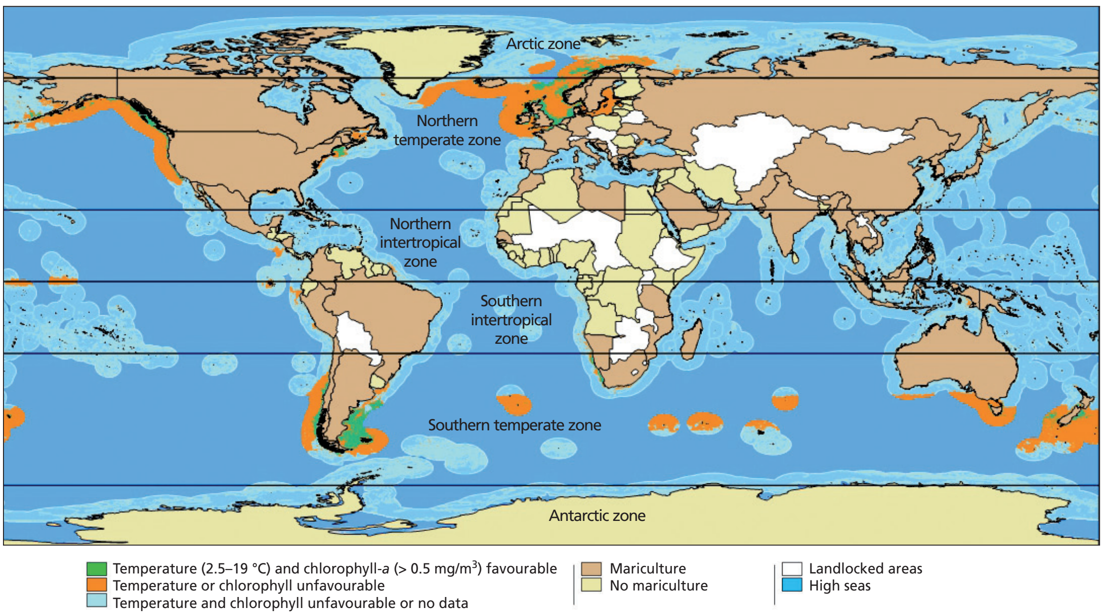
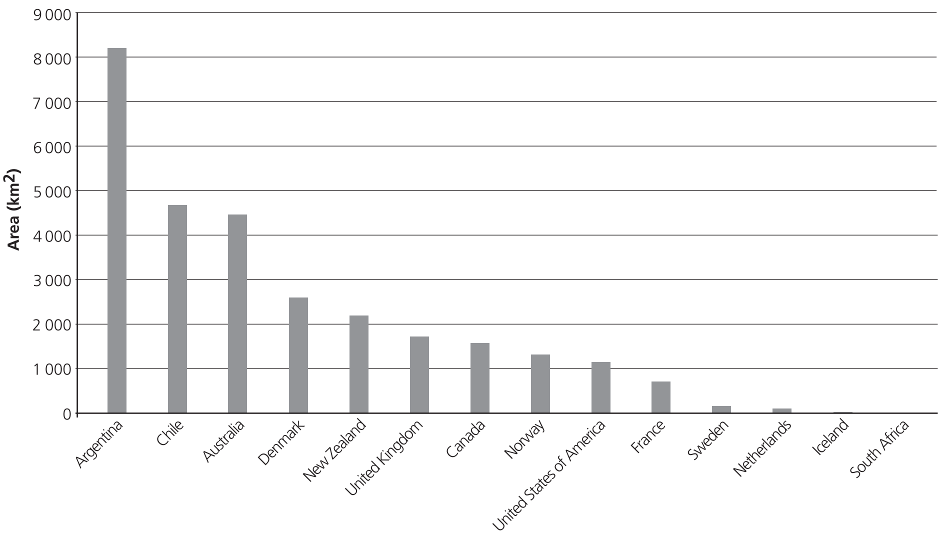


FIGURE 32
Ranking by area of main mariculture nations with temperatures and chlorophyll-*a* concentrations favourable for blue mussel grow-out and depths and current speeds suitable for longlines



Potential for IMTA of Atlantic salmon and blue mussel was found among nine nations in a total of 14 590 km^2 (Table 5). The area with potential for IMTA is less than the area for either species because it is defined by the portions of the temperature ranges that overlap one another (2.5–16 °C), as well as including the chlorophyll-*a* threshold for the blue mussel. The Argentine Republic and the Republic of Chile stand out area-wise (Figure 33), while New Zealand and the other nations possess much less suitable area (Figure 34).

FIGURE 33
Regional view of areas in southern Latin America with temperatures and chlorophyll-*a* concentrations favourable for Atlantic salmon-blue mussel IMTA and depths and current speeds suitable for sea cages and longlines

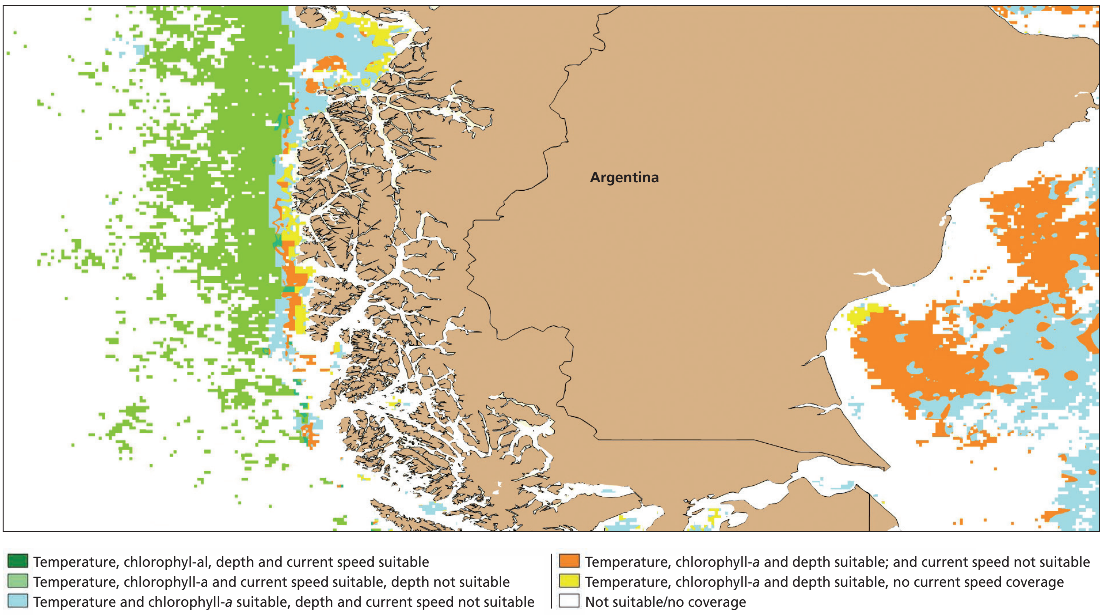
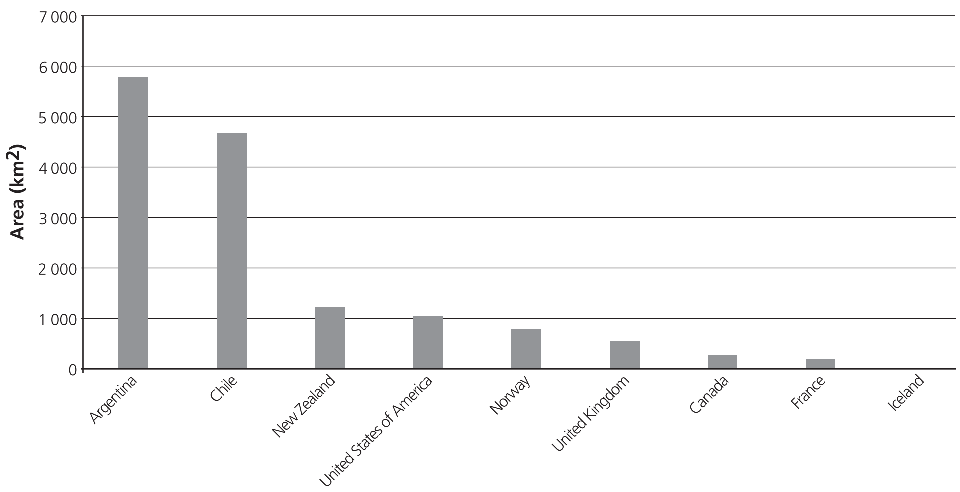


FIGURE 34
Ranking by area of main mariculture nations with temperatures and chlorophyll-*a* concentrations favourable for Atlantic salmon-blue mussel IMTA and current speeds and depths suitable for sea cages and longlines



4.3.2 Spatial integration of areas with favourable grow-out for fish and mussels with areas technically feasible for cages and longlines and within the cost-effective area for development

Integrating the cost-effective area for development – the area within 25 nm (46.3 km) of a port that is within an EEZ - with potential for cobia in terms of temperature, depths and current speeds for cages provides an estimate of potential that emphasizes the operational dependence of offshore culture installations on the proximity to essential onshore facilities, as well as the distance limit to maintain economic viability of the operation. The introduction of this new, but nevertheless important criterion, changes the results for cobia, Atlantic salmon, blue mussel and IMTA already reported above in Table 5 in that the areas that satisfy all of the criteria are much reduced, especially for countries that have relatively few ports listed in the World Port Index (2009) (Table 6).

TABLE 6
Number of nations and corresponding areas within the cost-effective area for development integrated with favourable grow-out for cobia, Atlantic salmon, blue mussel and IMTA and depths and current speeds suitable for sea cages and longlines

Grow-out, technical, and cost-effective area criteria	Mariculture nations		Non-mariculture nations		Total	
	Nations	Area (km^2)	Nations	Area (km^2)	Nations	Area (km^2)
Cobia	42	66 188	34	31 004	76	97 192
Atlantic salmon	6	2 447	0	0	6	2 447
Blue mussel	11	5 848	0	0	11	5 848
IMTA	6	1 202	0	0	6	1 202

In the case of cobia, taking into account the cost-effective area for development reduces cobia potential among mariculture countries to 66 188 km², about 10 percent of that when cost-effective area is not considered, but the number of countries with potential is reduced by only two to 42 (Table 6). Among the mariculture countries, the Republic of India, the Federative Republic of Brazil and the Republic of Indonesia stand out (Figures 35a and 35b). Among the non-mariculture nations, the total area is 31 004 km² with 34 nations possessing potential for cobia. The Federal Republic of Nigeria stands out, and the Bolivarian Republic of Venezuela and the Republic of Liberia possess the next most abundant area in this category (Figures 36a and 36b). Viewed from a regional and subregional perspective, potential for cobia is widely distributed with the largest potential in Southeastern Asia, South America and Eastern Africa (Table 7).

FIGURE 35a
Ranking by area of main mariculture nations in cost-effective area for development, temperatures favourable for offshore grow-out of cobia and current speeds and depths suitable for sea cages

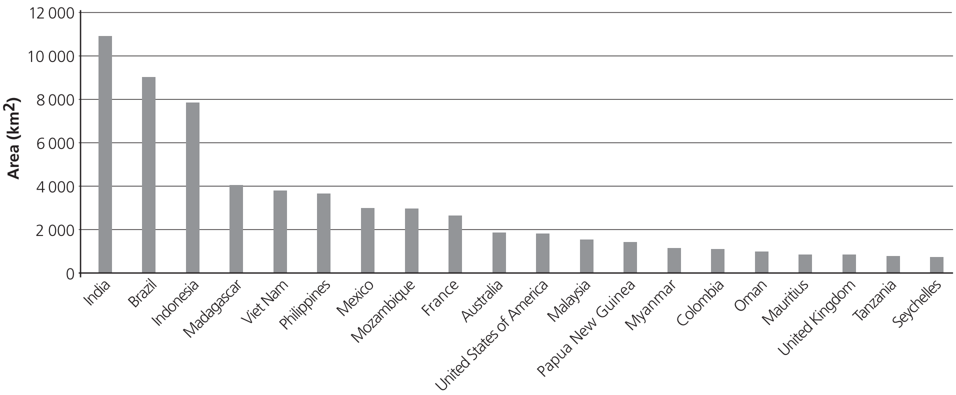


FIGURE 35b
Ranking by area of main mariculture nations in cost-effective area for development, temperatures favourable for offshore grow-out of cobia and current speeds and depths suitable for sea cages

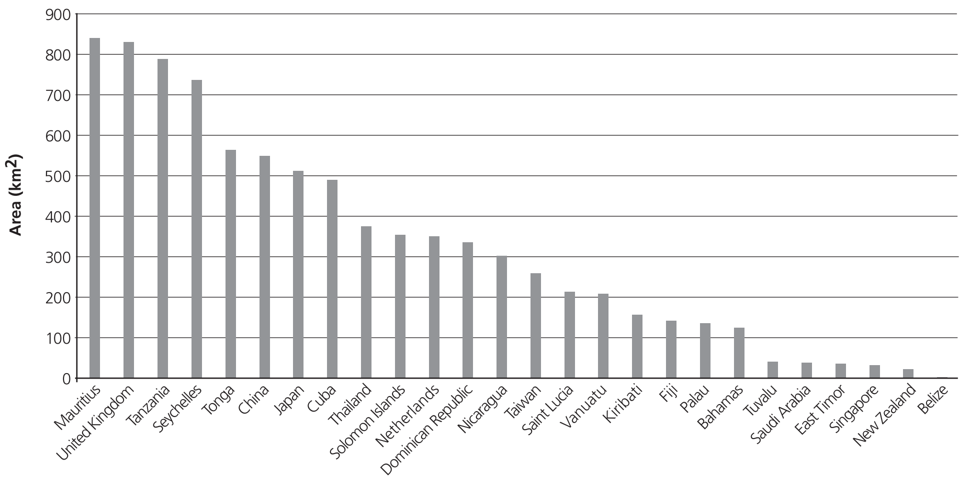


FIGURE 36a

Ranking by area of main non-mariculture nations in cost-effective area for development, temperatures favourable for offshore grow-out of cobia and current speeds and depths suitable for sea cages

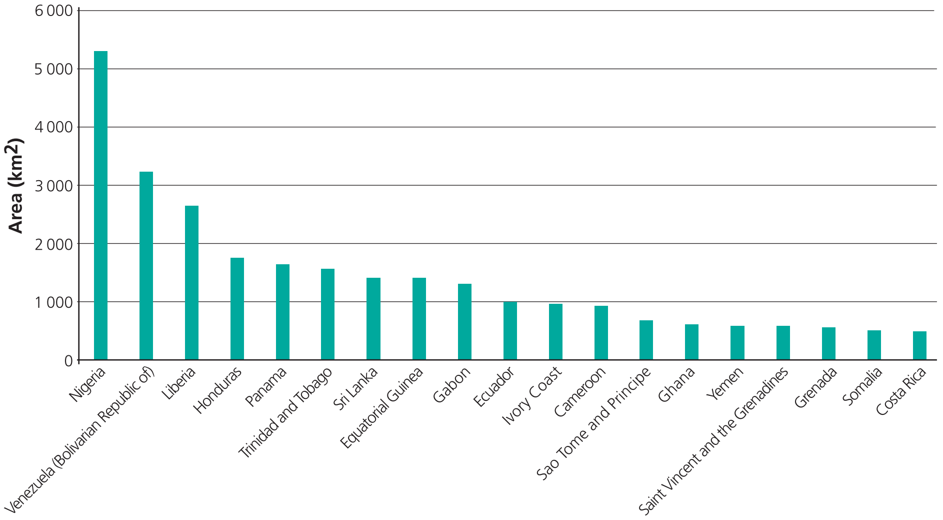


FIGURE 36b

Ranking by area of main non-mariculture nations in cost-effective area for development, temperatures favourable for offshore grow-out of cobia and current speeds and depths suitable for sea cages

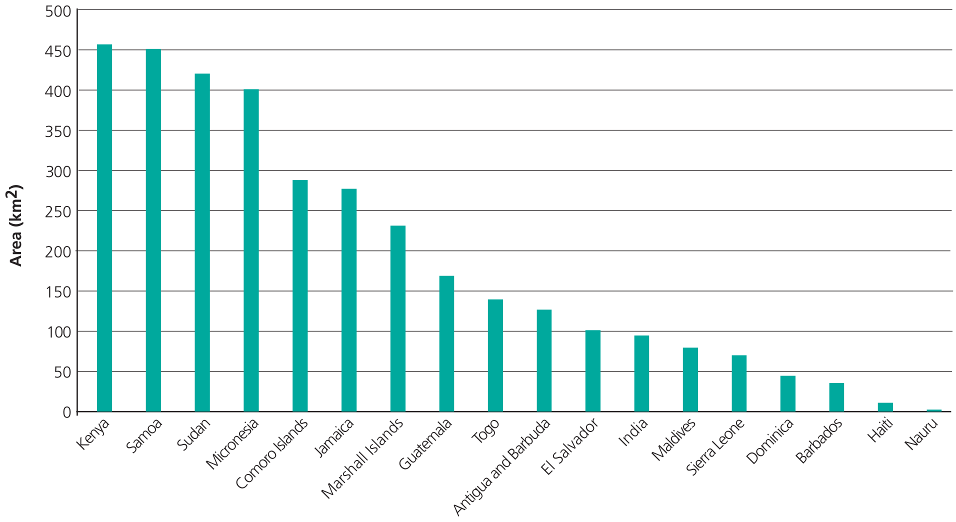


TABLE 7
Estimates of mariculture potential for cobia by regions and subregions

Regions/ subregions	Sum of area (km^2)
Asia	33 955
Southeastern Asia	18 489
Southern Asia	12 542
Western Asia	1 605
Eastern Asia	1 319
Americas	29 614
South America	14 838
Central America	7 451
Caribbean	6 663
Northern America	662
Africa	26 021
Eastern Africa	11 030
Western Africa	10 241
Middle Africa	4 329
Northern Africa	421
Oceania	7 601
Melanesia	2 636
Polynesia	2 254
Australia and New Zealand	1 785
Micronesia	927
Total	**97 192**

Taking into account the cost-effective area for development for Atlantic salmon among mariculture nations results in a total area of 2 447 km^2 among six nations, with the United States of America and the Kingdom of Norway dominant (Figure 37).

Potential for the blue mussel within the cost-effective area for development is 5 848 km^2 among 11 mariculture nations. The Kingdom of Denmark and the United Kingdom of Great Britain and Northern Ireland stand out (Figure 38).

Potential for IMTA within the cost-effective area for development amounts to only 1 202 km^2 among six nations, dominated by the United States of America and the Kingdom of Norway (Figure 39). A Southern Hemisphere territory accounts for a part of the potential of the United Kingdom of Great Britain and Northern Ireland.

FIGURE 37
Ranking by area of main mariculture nations within the cost-effective area for development, with temperatures favourable for Atlantic salmon grow-out and current speeds and depths suitable for sea cages

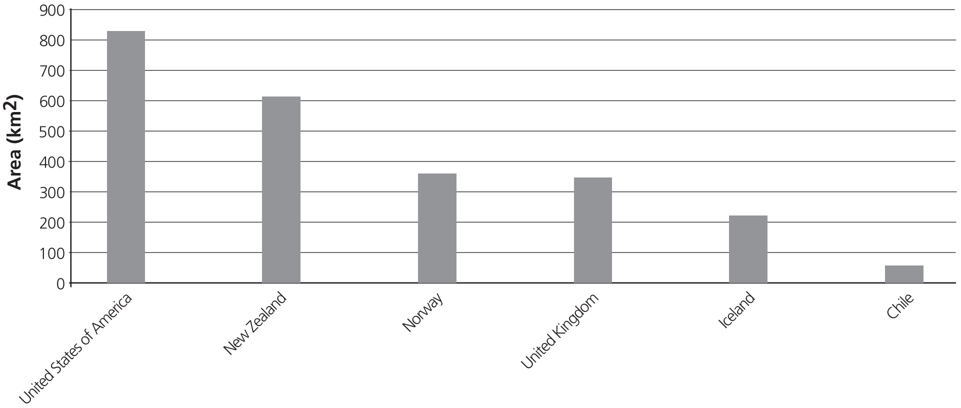


FIGURE 38
Ranking by area of main mariculture nations within the cost-effective area for development, with temperature and chlorophyll-a concentration favourable for blue mussel grow-out and current speeds and depths suitable for longlines

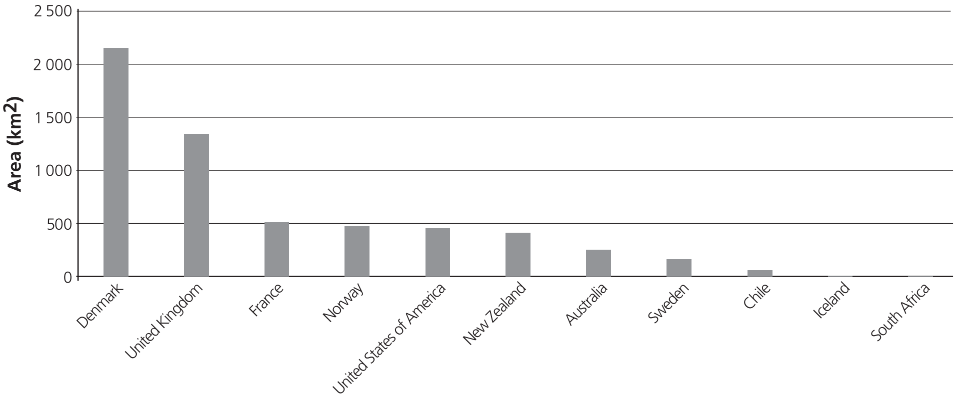
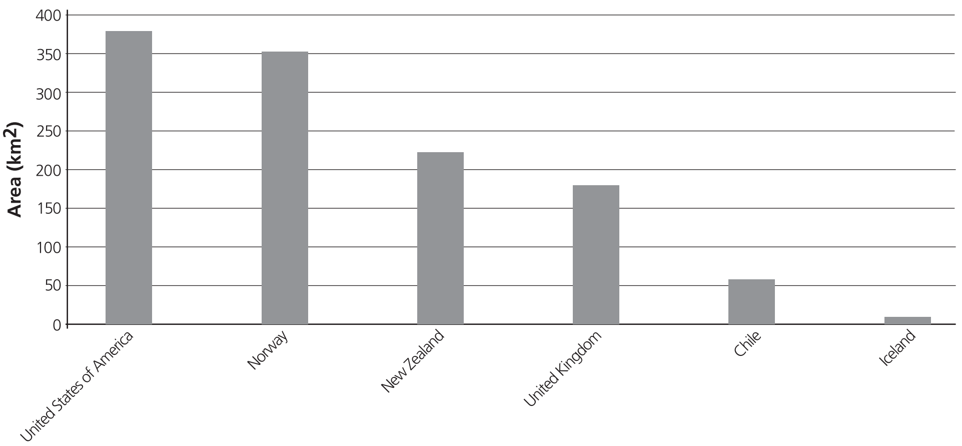


FIGURE 39
Ranking by area of main mariculture nations within the cost-effective area for development, with temperatures and chlorophyll-*a* concentration favourable for Atlantic salmon-blue mussel IMTA and current speeds and depths suitable for sea cages and longlines



4.4 Hypothetical loss of offshore mariculture potential due to competing and conflicting uses

In addition to offshore mariculture, there is a host of potentially competing and conflicting uses for the water surface, water column, bottom and sub-bottom. Most of these alternative uses fall within central or local government administration and regulation, but some may be international in scope. The objective for mariculture development is to avoid or minimize the competing and conflicting uses while identifying adjacent uses that would be complementary. Complementary uses currently under discussion include wind-farm supporting structures, wave energy, and unused oil or gas platforms, but areas closed to fishing need not be off-limits to mariculture. Similarly, there are possible competing and conflicting uses of the space needed for onshore mariculture support facilities, with many alternative uses for the space required. In contrast to the offshore situation, sites for onshore facilities are likely to be under the jurisdictions of local authorities.

Marine protected areas (MPAs) (IUCN and UNEP-WCMC, 2010) provide an example of alternative uses of space possibly conflicting, or alternatively, possibly offering complementary opportunities for mariculture. MPAs were selected because the database is global and because MPAs can be both national and international in scope.

Based on an analysis of the 2010 MPA data (IUCN and UNEP-WCMC, op. cit.), there are about 3.8 million km^2 devoted to MPAs worldwide. Nearly all of the MPA area of 3.5 million km^2 is among 71 mariculture nations, while the remainder is among 49 non-mariculture nations (Table 8). The mariculture nations with the greatest MPA expanses are the United States of America and Australia (Figure 40), with the Republic of Ecuador possessing by far the largest area among non-mariculture nations (Figure 41).

TABLE 8

Number of nations and corresponding MPA area, and nations and corresponding areas within MPAs with potential for cobia offshore mariculture

Criteria	Mariculture nations		Non-mariculture nations		Total	
	Nations	Area (km^2)	Nations	Area (km^2)	Nations	Area (km^2)
MPAs	71	3 533 612	49	296 957	120	3 830 569
Temperatures suitable for cobia and depths and current speeds suitable for cages inside MPAs	31	44 863	12	2 092	43	46 955

In order to illustrate the effect of other uses on mariculture potential, it is assumed here that all of the area that is suitable for cobia culture in terms of temperature favourable for growth, depths and current speeds for cages, and that is also within national MPAs that are themselves within economic zones, is excluded from the development of offshore mariculture.

The outcome is that, altogether, cobia potential would be reduced by nearly 47 000 km^2, amounting to about 6 percent of the total potential that was identified without regard to conflicting, competing or complimentary uses (Section 4.3).

However, cobia potential among mariculture nations would be reduced by 7 percent, while that of non-mariculture nations would be reduced by only 2 percent. Thirty-one mariculture practising nations would stand to lose some potential (Table 8).

FIGURE 40
Ranking by area of main mariculture nations in marine protected areas

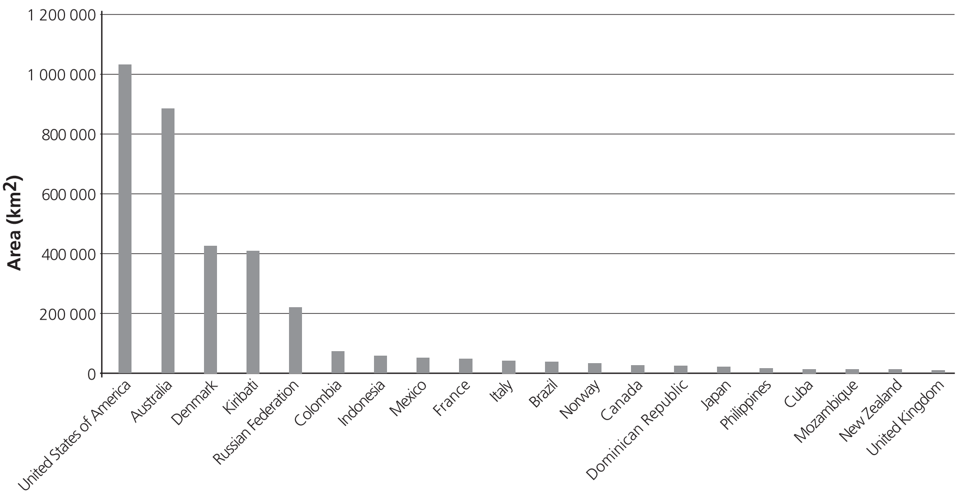
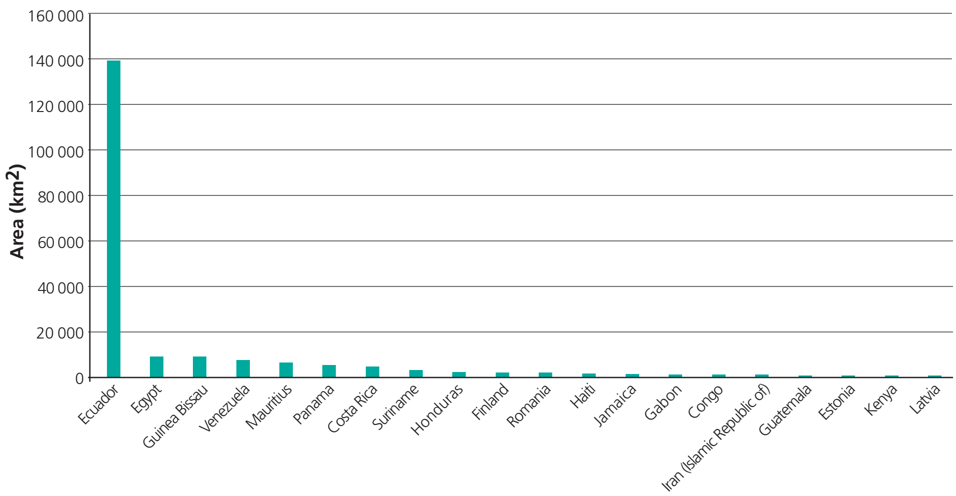


FIGURE 41
Ranking by area of main non-mariculture nations in marine protected areas



Australia, the United States of America and the Republic of Indonesia would lose the greatest amounts of area with potential for the mariculture of cobia (Figure 42; Figure 43). Twelve non-mariculture nations also would lose some cobia mariculture potential (Table 8), and those most affected would be the Arab Republic of Egypt, the Republic of Costa Rica and the Republic of Honduras (Figure 44).

Looking more broadly at the loss of areas with potential for mariculture development that is due to competing and conflicting uses, the countries that would most likely be affected would be those nations not only with the largest expanses of MPAs, but also those with already developed multiple uses of maritime areas, such as for mineral resources extraction (oil, metals), well-developed commercial, artisanal and recreational fisheries, and large, busy ports.

FIGURE 42
Regional view of area within MPAs with temperatures favourable for cobia grow-out and depths and current speeds suitable for sea cages

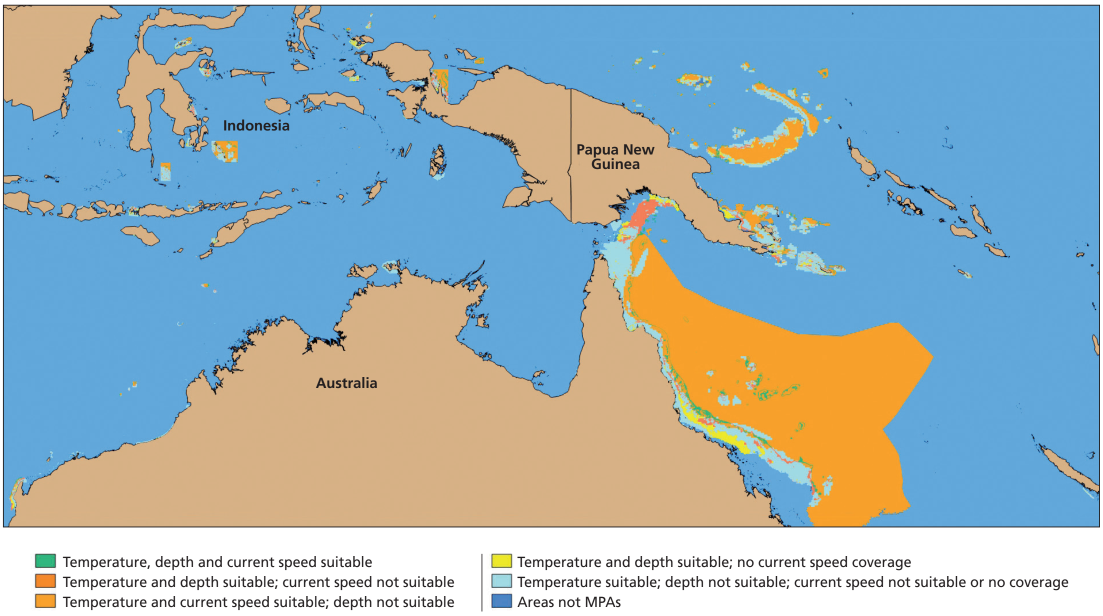


FIGURE 43
Ranking by area of main mariculture nations in hypothetical loss of area with potential for offshore mariculture of cobia due to exclusion from MPAs

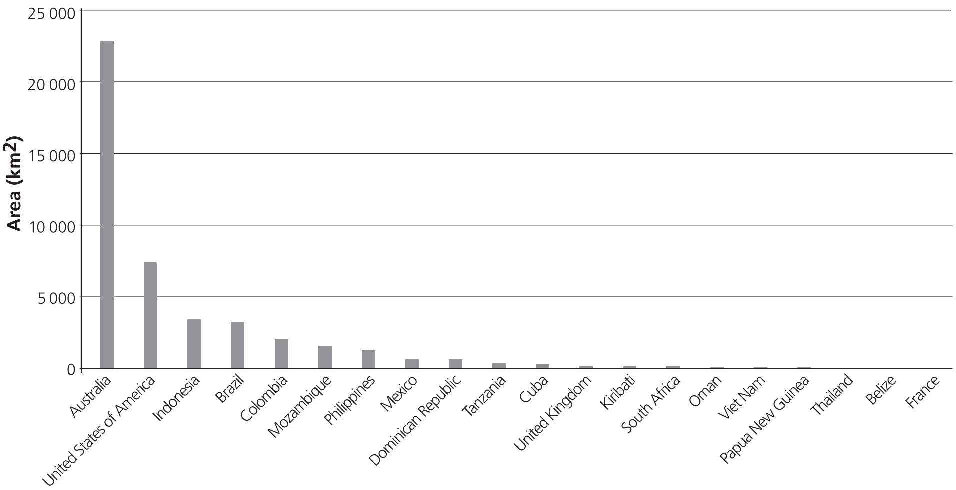
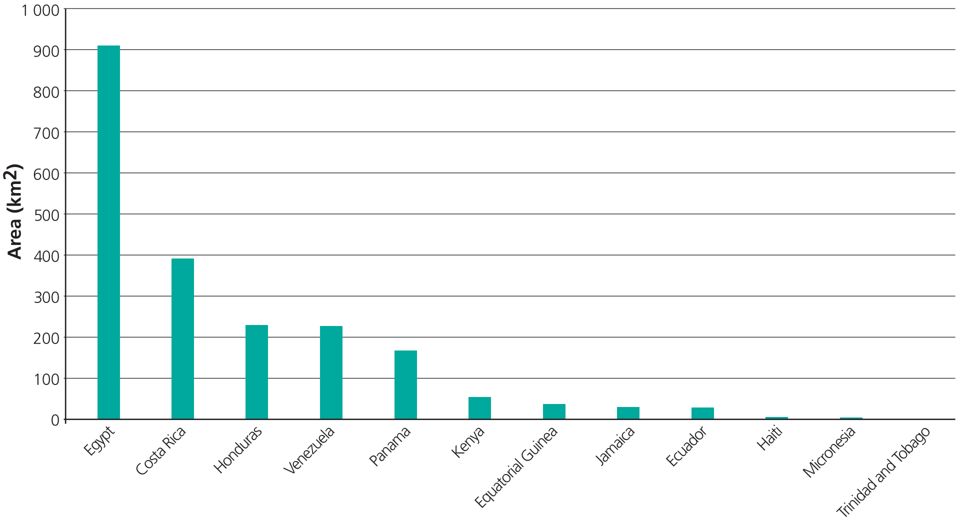


FIGURE 44
Ranking by area of main non-mariculture nations with a hypothetical loss of area with potential for offshore mariculture of cobia due to exclusion from MPAs



4.5 Summary of the results on offshore mariculture potential with species, culture systems and cost-effective area for development integrated

The salient results on offshore mariculture potential from this section are summarized in the following paragraph and supported by results shown in Figures 45 and 46.

(i) Integration of basic criteria for cage and longline culture systems (depth, current speed) with criteria for favourable grow-out of cultured animals (temperature, food availability as chlorophyll-*a* for the mussel) indicates large areas globally, among many nations, with potential for development of offshore mariculture.

(ii) Apart from the species used here to represent potential, the results are also indicative of offshore mariculture potential for other species with similar temperature and chlorophyll-*a* requirements for grow-out and with cage and longline culture system requirements similar to those as specified in this document.

FIGURE 45
Area suitable for offshore mariculture of cobia, Atlantic salmon, blue mussel and IMTA among mariculture nations overall and within the cost-effective area for development

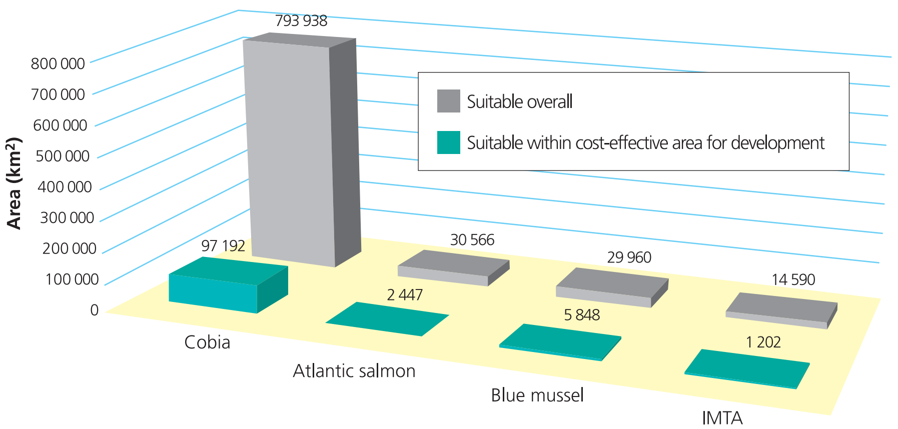
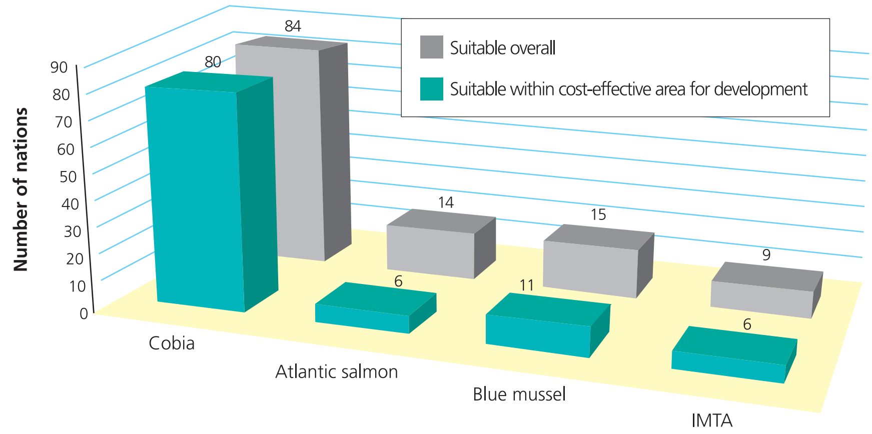


FIGURE 46
Numbers of nations with areas suitable for offshore mariculture of cobia, Atlantic salmon, blue mussel and IMTA among mariculture nations overall and within the cost-effective area for development



(iii) Even when further constrained by including the cost-effective for area for development as an additional criterion, large areas with potential for offshore mariculture development remain and the potential is found among many nations.

(iv) Among the species, potential for cobia is much greater than that for the Atlantic salmon, blue mussel and IMTA, both in terms of the number of nations with potential and in terms of sea-surface area. This result suggests that there is greater offshore mariculture potential for species that can be grown out in warm temperate and tropical waters (e.g. Figure 25) than for those species with cool and cold temperate grow-out regimes (e.g. Figures 29 and 31). However, actual future offshore production may differ from the estimates of potential herein owing to the influence of the many factors not included in this study.

(v) Hypothetically, setting aside MPAs as zones excluding offshore cobia mariculture resulted in a minimal loss of potential in area and in terms of number of nations; however, this is only one among many possible competing or conflicting uses for marine space. Thus, it can be expected that many additional offshore waters with potential for offshore mariculture will be out of reach or in contention.

5. Comparisons and verifications for offshore mariculture potential

Estimates of offshore mariculture potential require verification to improve the design of future investigations and to be credible for development planning. The main issue with the verification of the results of this study is that potential for the development of offshore mariculture is being estimated where it largely does not yet exist. Thus, there were few opportunities to directly verify the results that would be used to compare areas found suitable for offshore mariculture with actual offshore mariculture locations. As a consequence, predictions of potential were examined through three kinds of comparisons based on the offshore potential found for each of the three species-culture system combinations and IMTA. The comparisons were:

(i) **National-level potential and production comparison:** Offshore mariculture potential in square kilometres compared with the mariculture production of nations already practising mariculture of the species-culture system combination at the national level.

(ii) **National to local level offshore mariculture potential compared with inshore mariculture locations:** These were comparisons on maps at the national level to the local level of areas found to have offshore potential compared with either the actual locations of inshore mariculture installations of the species (e.g., Figures 47a and b) or with inshore farming areas in which mariculture of the species was being practised.

(iii) **Offshore mariculture potential compared with actual offshore mariculture locations:** These were comparisons on maps of areas with offshore mariculture potential with the actual locations of offshore installations. These comparisons are the actual verification of the results.

For these comparisons, emphasis was placed on meeting temperature thresholds for all three species, as well as the chlorophyll-*a* threshold for the blue mussel, as these were the environmental variables used to assess grow-out performance. However, depth and current speed criteria were also taken into account and reported.

5.1 COBIA

5.1.1 National-level potential and production comparison

Potential was found in all five of the nations reporting cobia culture to FAO (2010) (Table 9).

TABLE 9

National-level potential and production comparison for cobia: mean annual production (2004–2008) of cobia-producing nations with areas meeting temperature, depth and current speed criteria and areas meeting the first two criteria

Nation	Mean annual production 2004–2008 (tonnes)	Area with potential (km^2)	
		Temperature, depth and current speed	Temperature and depth
China	19 982	13 208	53 137
Taiwan Province of China	3 140	3 472	4 573
Belize	384	99	1 702
Mayotte (France)	5	430	593
Singapore	4	32	176

5.1.2 National to local level offshore mariculture potential compared with inshore mariculture locations

At local levels comparison data were available from eight nations, with cobia locations that spanned the latitudes from 8° to 24°N and one at 8°S. Among the eight nations, locations were obtained for 22 cage sites and nine cobia-farming areas, of which 27 are listed in Tables 10 and the remaining 4 in Table 11.

Two cage sites in the People's Republic of China, both in the south of Hainan Island, met the 22–32 °C favourable grow-out threshold, but 5 farming areas in the Socialist Republic of Viet Nam and 1 farming area in the Taiwan Province of China had temperatures seasonally too cool that did not meet the threshold.

The cage sites in the People's Republic of China that did not meet the temperature threshold (Table 10) suffered from unseasonably low (13 °C) temperatures that killed cobia in the early spring of 2008 (C. Zhou, personal communication, 2011).

The areas offshore from these inshore farm locations had temperatures below the 22 °C threshold from December through March over the long term of the 17-year data set. Unfortunately, the actual temperature data that were available at only one inshore cage site did not cover the coolest months of the year, January to March. The two cobia culture areas that were within the favourable grow-out temperature threshold were on the south side of Hainan Island, the southernmost part of the country (Tables 10 and 11, Figure 47f).

Cobia are raised in four main regions in the Socialist Republic of Viet Nam. Beginning in the north, cobia are raised in Hai Phong and Quang Ninh provinces, then further south in Nghe An and Khanh Hoa provinces, and finally in the southernmost location in Vung Tau province (Svennevig and Huy, 2005). Seasonally low temperatures that put cobia at risk during the winter season were indicated for the Hai Phong, Quang Ninh and Nghe An province farming areas in the north of the Socialist Republic of Viet Nam. The temperature range in the northern portion of the country is given as 14–31 °C.

In presenting the grow-out pattern of cobia in sea cages in the Socialist Republic of Viet Nam, Nhu *et al.* (2009) indicate that growth does not occur when the temperature is less than 22 °C. The locations in Hai Phong and Quang Ninh provinces are below the 22 °C threshold from December to March, while the next farming area south in Nghe An province is borderline in January and below the threshold in February. For the purposes of this technical paper, these northern culture areas are deemed unsuitable because of the temperatures that are below the lower threshold limit of cobia grow-out potential of 22 °C.

There are two main cobia-farming areas in the Taiwan Province of China; one area is in the Penghu Islands (west central, offshore) and the other is in Pingtung County (southwest) (Hsu, Chen and Liao, 2005). Although the Penghu Island area falls outside of the temperature threshold range for the months of December through March, it lies just outside of and to the north of the area within the range. According to Liao *et al.* (2004), in central Taiwan Province of China overwintering is a problem for grow-out cages, especially in the Penghu Islands.

Water temperatures during the winter season can drop down to 16 °C. Growth of cobia is usually retarded at low temperatures, and sometimes high mortality also occurs when the temperature decreases to below 16 °C. As a result, the culture period in these sea-cage areas is longer (up to 17 months) compared with the sea-cage areas in southern Taiwan Province of China (11–14 months), where the water temperature range is between 23.5 and 28 °C all year around. According to Shih, Chou and Chiau (2009), the average temperature in the Penghu Islands is 25–27 °C in spring to autumn, declining to 21–22 °C in the winter, with a low temperature of 16 °C during the winter season. However, according to Miao *et al.* (2009), mid-winter temperatures in the Penghu Islands area can dip below 15 °C, resulting in heavy mortality while prevailing winter temperatures are around 18 °C.

At the two inshore farm locations in Belize (Figure 47c), at one offshore farm in the Republic of Panama (Figure 47d), and at one of two inshore farming areas in the Socialist Republic of Viet Nam, all three thresholds were met close offshore. At a cobia site in

Muttom, Tamil Nadu, the Republic of India, cobia cages have been established at a distance of about 0.6 km m from shore at 20 m depth (P. Anilkumar, personal communication, 2012; Anilkumar, 2012) in an area meeting the temperature threshold, but too shallow to meet the depth threshold of 25 m and with current speeds lower or higher than 10–100 cm threshold.

In the vicinity of Muttom, areas meeting all three thresholds are at least 13 km offshore. At the second farming area in the Socialist Republic of Viet Nam, all thresholds were met, but very distant from the inshore farming area (Table 10). Although the temperature and depth thresholds were met at one farming area in the southwest of the Taiwan Province of China and at one farm location near the Commonwealth of Puerto Rico, current speed coverage was lacking.

TABLE 10
Comparison of offshore potential of cobia with inshore cage sites and farming areas based on meeting the 22–32 °C temperature threshold

No.	Country or territory	Administrative unit	Location	Temperature threshold (22–32 °C) met (Y=Yes; N=No)	Cage site (CS) or farming area (FA)
1	Belize (Figure 47c)	Unknown	Marine Farms Belize, Site 1	Y	CS
2	Belize (Figure 47c)	Unknown	Marine Farms Belize, Site 2	Y	CS
3	China	Guangdong	Dapeng Bay, Huizhou	N	CS
4	China	Guangdong	Zhapo, Gang, Yangjiang	N	CS
5	China	Guangdong	Techeng Dao 1, Zhanjiang	N	CS
6	China	Guangdong	Wushi, Zhanjiang	N	CS
7	China	Guangdong	Dongli, Zhanjiang	N	CS
8	China	Guangdong	Liusha Gang, Zhanjiang	N	CS
9	China	Guangdong	Techeng Dao 2, Zhanjiang	N	CS
10	China	Guangxi	Bailong, Fangchenggang	N	CS
11	China	Guangxi	Tieshan Gang, Beihai	N	CS
12	China	Hainan	Xinying Gang, Lingao	N	CS
13	China	Hainan	Jinpai Gang, Lingao	N	CS
14	China	Hainan	Xinyingzhen	N	CS
15	China	Hainan	Lingshui, Sanya	Y	CS
16	India	Tamil Nadu	Muttom	Y	CS
17	Panama	Unknown	Panama Mariculture Company	Y	CS
18	Taiwan Province of China	Penghu County	Penghu Islands	N	FA
19	Taiwan Province of China	Pingtung County	Shiao-Liu-Chio	Y	FA
20	United States of America	Puerto Rico	Snapperfarm, Inc.	Y	CS
21	Viet Nam	Hai Phong	Hai Phong	N	FA
22	Viet Nam	Khanh Hoa	Van Phong Bay	Y	FA
23	Viet Nam	Nghe An	Cua Lo District	N	FA
24	Viet Nam	Nghe An	Quynh lap District	N	FA
25	Viet Nam	Quang Ninh	Ha Long Bay	N	FA
26	Viet Nam	Quang Ninh	Bai Tu Long Bay	N	FA
27	Viet Nam	Vung Tau	Vung Tau	Y	FA

Notes: Grey color indicates cage sites or farming areas that met the temperature threshold.

5.1.3 Offshore mariculture potential compared with actual offshore mariculture locations

Three of the four locations shown in Table 11 are well offshore (the Federative Republic of Brazil and the Republic of Panama), and the last one is offshore of Hainan Island, the People's Republic of China. These locations offer the opportunity for verification of predicted potential with actual offshore locations. Of the four, the location in the Republic of Panama met all criteria (Figure 47d). The Aqualider cage site in the Federative Republic of Brazil was well offshore and met two of the three criteria. It was just to the east of an area meeting all three criteria (Figure 47e). The MPA site is in the same vicinity as the Aqualider site and 6 km offshore (Figure 47 e). It is in an area meeting the grow-out temperature criterion, but is sited at 23m depth (R.Cavallii, personal communication, 2012) so would not meet the depth threshold and in an area where current speeds are too variable to meet the current speed threshold. The site in the People's Republic of China on the south side of Hainan Island was closely adjacent to an area meeting temperature and depth criteria, but lacked current speed coverage. There is an area meeting all criteria lying further east (Figure 47f).

TABLE 11
Cobia mariculture locations that are offshore

No.	Country or territory	Administrative unit	Location	Temperature threshold (22–32 °C) met (Y=Yes; N=No)	Cage site (CS) or farming area (FA)
1	Brazil (Figure 47e)	Recife	Aqualider	Y	CS
2	Brazil (Figure 47e)	Recife	MPA	Y	CS
3	Panama (Figure 47d)	Unknown	Open Blue Sea Farm	Y	CS
4	China (Figure 47f)	Hainan	Jiu Suocun	Y	CS

Note: Grey color indicates cage sites or farming areas that met the temperature threshold.

FIGURE 47a
Cobia cages in site 1 near Belize City, Belize

Location: 17°21’11.00”N, 88°10’22.42”W

FIGURE 47b
Cobia cages in site 2 near Belize City, Belize

Location: 17°18’28.05”N, 88° 9’57.91”W

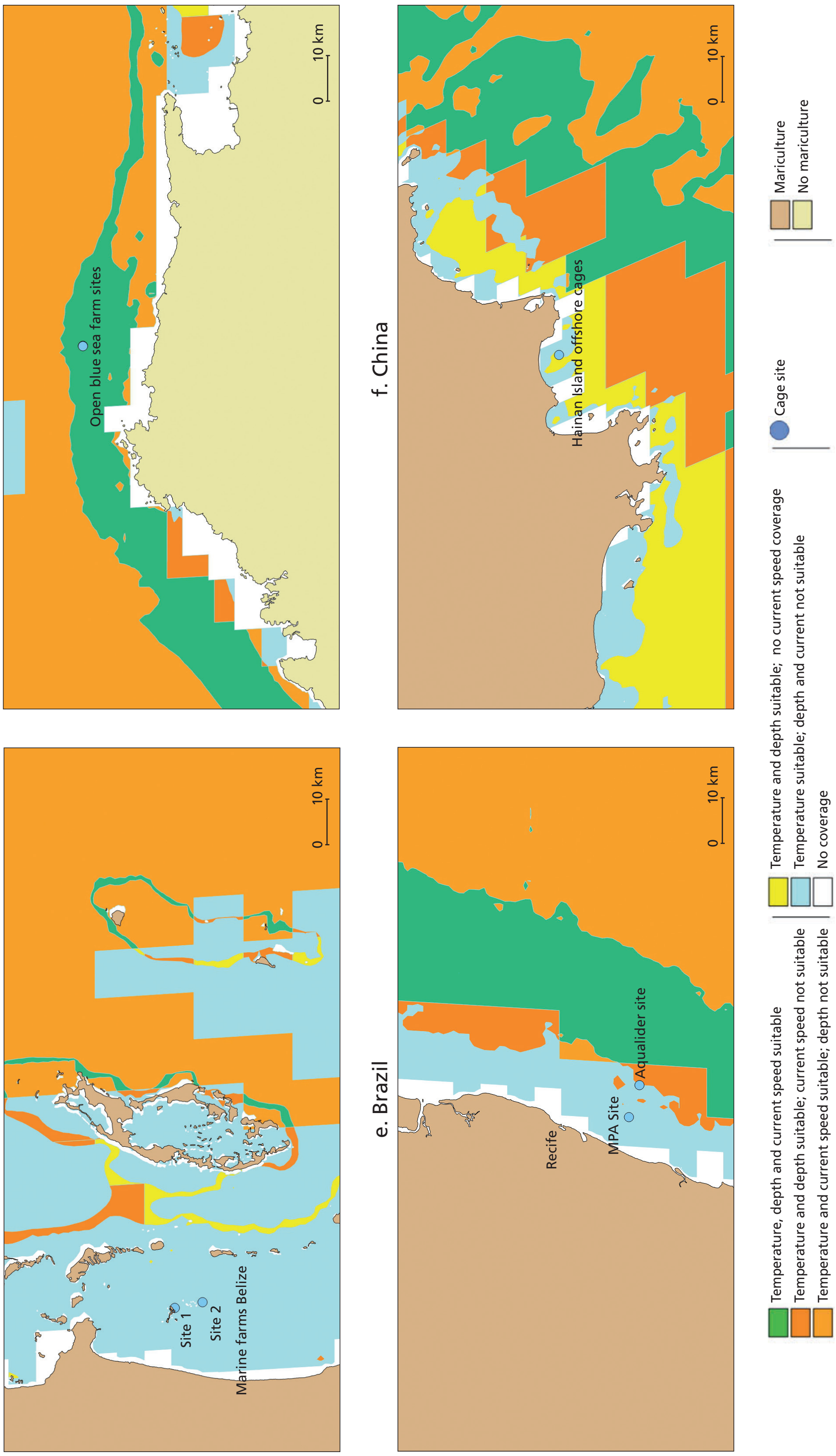
Notes:
Marine Farms Belize has two concessions; in the lagoon and mangrove areas, and in an exposed area. Although the two sites appear similar in Figure 47c, Site 1 in Figure 47a is somewhat sheltered while Site 2 in Figure 47b is in open waters and has more consistent water quality to Site 1.

Cage site water temperatures vary between average 26°C in the winter months (December–March), to 30–31°C in the peak of the summer (June–September). Depth in the cages sites reach 20 metres, and current is variable but mainly north to south with peaks of 0.5 knots and days of slack current. The feed barge in Site 2 can hold 100 tonnes of pellets, and is equipped with generators and blowers for automatic feeding, as well as a house for the guard and workers.

Source notes: J. Alarcon (personal communication, 2012).
Source images: © 2012 Google, Image © 2012 Digital Globe.

FIGURE 47c, d, e, f

Areas with temperatures favourable for grow-out of cobia and depths and current speeds suitable for sea cages compared with locations of cobia sea cage sites



5.2 ATLANTIC SALMON

5.2.1 National-level potential and production comparison

The comparison of national-level offshore potential for Atlantic salmon with production showed that among the 14 nations and territories already producing Atlantic salmon, offshore potential with all three criteria met was found among seven (Table 12). Three of the nations for which potential meeting all three criteria was not found are small producers (1 to 158 tonnes), but a fourth, Australia, is becoming important. Additionally, offshore potential was identified for seven nations or territories not yet producing Atlantic salmon. It is interesting to note that in the Kerguelen Islands territory (Table 12), Atlantic salmon were introduced more than 25 years ago and the population still persists (Ayllon *et al.*, 2004).

A comparison among nations and territories meeting all three criteria and those meeting two criteria indicates that current speed is the criterion limiting potential. This result is affirmed in that, when only temperature and depth are considered, offshore potential is lacking in only two nations (the Kingdom of Spain and the Kingdom of Denmark) of the fourteen nations and territories (Table 12). These are nations with the least quantities of production, suggesting that conditions for inshore Atlantic salmon production may not be favourable there or that space with potential is limited.

TABLE 12
National-level comparison of Atlantic salmon annual production with potential by nation tabulated as areas meeting two temperature threshold ranges as well as depth and current speed criteria, and areas meeting the first two criteria

No.	Nation or national territory	Mean annual production 2004–2008 (tonnes)	Potential (km^2) by temperature threshold			
			Depth and current speed are suitable		Depth is suitable	
			4–16 °C	1.5–16 °C	4–16 °C	1.5–16 °C
1	Norway (Figure 48a)	653 483	594	912	33 083	41 856
2	Chile (Figure 48d)	365 636	10 011	10 022	53 249	54 184
3	United Kingdom	135 749	606	606	150 568	150 568
4	Canada (Figure 48c)	103 957	284	284	25 397	32 253
5	Denmark (Faroe Islands)	26 762	0	0	6 274	6 274
6	Australia	21 008	0	0	1 335	1 335
7	United States of America	12 546	1 120	2 945	44 595	161 715
8	Ireland (Figure 48b)	11 786	0	0	27 393	27 393
9	Iceland	3 412	427	600	8 702	21 729
10	France	1 103	0	0	1 373	1 373
11	Russian Federation	158	0	0	0	720
12	Spain	12	0	0	0	0
13	Denmark	1	0	0	0	0
14	New Zealand	Unknown quantity**	2 826	2 826	25 412	25 412

No.	Nation or national territory	Mean annual production 2004–2008 (tonnes)	Potential (km^2) by temperature threshold			
			Depth and current speed are suitable		Depth is suitable	
			4–16 °C	1.5–16 °C	4–16 °C	1.5–16 °C
Potential of nations or territories not producing Atlantic salmon						
1	Argentina	0	6 454	6 454	145 503	150 851
2	South Africa (Prince Edward Island)	0	610	610	618	620
3	Australia (Macquarie Island)	0	51	190	64	258
4	France (Crozet Island)	0	1 163	1 814	1 751	2 682
5	France (Kerguelen Islands)	0	0	2 601	0	12 605
6	United Kingdom (the Falkland Islands [Malvinas]	0	421	424	23 796	23 976
7	United Kingdom (Tristan Da Cunha)	0	279	279	405	405

**Atlantic salmon have been introduced to New Zealand, but only Chinook salmon (*Oncorhynchus tshawytscha*) is successfully farmed on a significant scale there (New Zealand salmon farmers association; www.salmon.org.nz).

Note: Grey colour is used to indicate the seven countries that met the depth and current speed criteria.

5.2.2 National to local level offshore mariculture potential compared with inshore mariculture locations

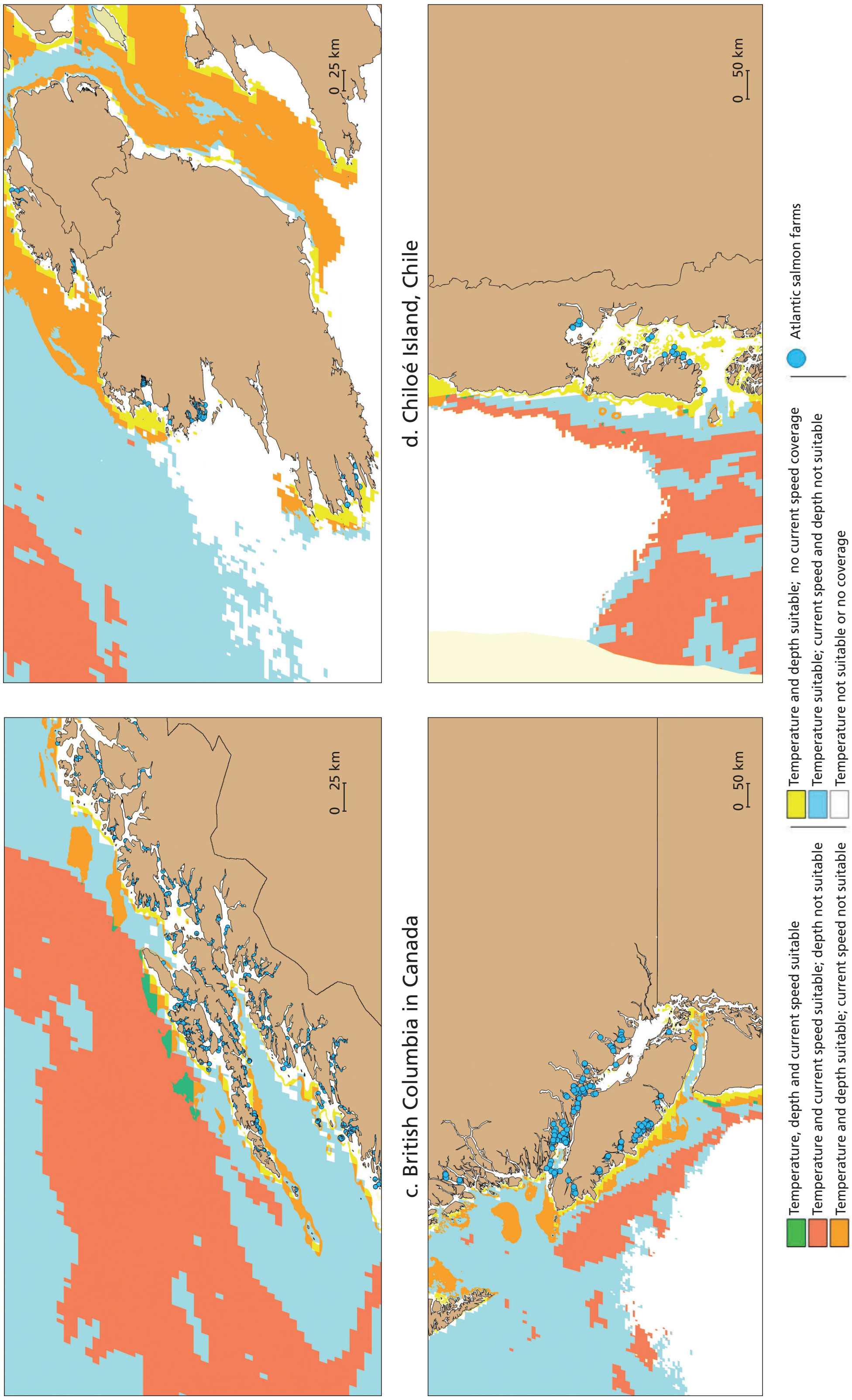
The comparison of offshore mariculture potential of Atlantic salmon with inshore farm locations was accomplished by visually comparing individual cage sites for the Kingdom of Norway, western Ireland, British Columbia in Canada, and for a part of the Republic of Chile with offshore areas meeting various combinations of thresholds (Figures 48a–d). Atlantic salmon farms are distributed all along the coast of the Kingdom of Norway, well into the Arctic Climate Zone, and the growth-temperature criterion is met in those nearshore areas where there is data coverage. In the areas with off-lying islands in the Kingdom of Norway, there are farms in areas meeting offshore temperature and depth criteria and there are areas nearby meeting all criteria (Figure 48a). In western Ireland, as in the Kingdom of Norway, nearly all of the Atlantic salmon farms are in sheltered waters (Figure 48b). There are many areas just offshore of the inshore salmon farming areas that meet both temperature and depth criteria, and otherwise much of the offshore area possesses temperatures suitable for Atlantic salmon. However, no areas in western Ireland meet all three criteria. In British Columbia, Canada, temperature and depth criteria were met along the west coast of Vancouver Island just offshore of the salmon farms that are located in sheltered waters (Figure 48c). Temperatures are suitable in an area in the northeast portion of Vancouver Island close to the mainland. The areas meeting all criteria are just south of the border with the United States of America as well as northwest of the area in which Atlantic salmon are currently farmed in western Canada.

Atlantic salmon are also farmed in eastern Canadian provinces, as far south as New Brunswick and nearby in northeast Maine (United States of America), and as far north as Newfoundland; however, no potential was found in those areas because of temperatures not meeting the threshold. As explained in Chapter 4, mean monthly temperatures in the Maine to Newfoundland areas from February through April were below the initial threshold of 4 °C. This prompted a re-evaluation of the temperature threshold. Actual temperatures at Atlantic salmon farms in this region were acquired. Also, mean monthly temperatures obtained from the spatial data archive at locations offshore of the most exposed culture sites were sampled. Accordingly, the lower threshold was decreased to 1.5 °C (Table 12) to better reflect the lower temperature limit of culture practice in this region. As a consequence, the Maine, Nova Scotia and New Brunswick areas were identified as having offshore potential consistent with inshore mariculture practice there, but not in Newfoundland. With the lower threshold extended to 1.5 °C, the area with potential is increased for most countries and territories (Table 12).

Potential for Atlantic salmon offshore farming occurs along most of the coast of the Republic of Chile, with the largest areas that meet all criteria being in the south. However, the area for which farm locations are available is relatively small and the farms are in inshore sheltered locations (Figure 48d). There, temperature and depth criteria are met in much of the area proximate to the farms as well as along the coast open to the ocean, and there are also small areas meeting all three criteria offshore. Additionally, temperatures are suitable for Atlantic salmon in the remaining areas.

FIGURE 48a,b,c,d

Areas with temperatures favourable for grow-out of Atlantic salmon and depths and current speeds suitable for sea cages compared with locations of salmon farms in Norway, Ireland, Canada and Chile



5.3 BLUE MUSSEL

5.3.1 National-level potential and production comparison

Fifteen nations and territories produced blue mussel in the 2004–2008 period, but potential, as estimated through meeting temperature, chlorophyll-*a*, depth and current speed thresholds, was found in only seven of them in relatively small areas except for the Argentine Republic (Table 13). Temperatures (4–18 °C) and depths for longlines (25–100 m) among the most important producer countries, all European nations, were suitable. Eastern Canada, including Prince Edward Island, Nova Scotia, New Brunswick, Newfoundland and Quebec provinces, is Canada's major mussel farming region (Canadian Aquaculture Industry Alliance, 2010). Blue mussels are also cultured in that region in Maine, the state adjacent to Canada, in the United States of America (New England Aquarium, 2010). However, as with Atlantic salmon, no blue mussel potential was found in that region, and for the same reason: winter temperatures that are below the 4 °C threshold range. In a similar fashion to Atlantic salmon, actual temperatures at an experimental offshore blue mussel farm in this region were acquired, and mean monthly temperatures in the spatial data archive at locations of several offshore culture sites were sampled in order to determine the long-term offshore monthly means. Accordingly, the lower threshold was decreased to 2.5 °C, while the upper threshold was extended to 19 °C to better reflect the temperatures experienced in culture practice in this region. As a consequence, the Maine, Nova Scotia and New Brunswick areas were identified as having potential consistent with mariculture practice there, but not in the more northern mussel-growing provinces.

The coastal chlorophyll-*a* criterion of concentrations greater than 1 mg/m^3 limited estimates of potential in the European region among the blue-mussel-producing nations, particularly in Ireland and the Kingdom of Norway (Table 13). According to R. Langan (personal communication, 2009), excellent growth and good condition are obtained in the open ocean at chlorophyll-*a* concentrations of 0.5 to 2 mg/m^3 at an experimental site 10 km offshore in the Gulf of Maine. At that site seven cohorts of blue mussels had been grown to a marketable size with an average production cycle of 13 months, which corresponded to good growth (Langan and Horton, 2005). No online actual chlorophyll-*a* measurement data were available for that site, but the spatial database for coastal chlorophyll was queried at the location of the experimental farm and the result was that the lowest mean monthly chlorophyll-*a* concentration was 0.5 mg/m^3 over seven years. Additionally, other offshore experimental farms are being established in the area, and a newly established commercial offshore mussel farm nearby the experimental site is proving to be successful. With these indications, the coastal chlorophyll-*a* threshold was decreased to concentrations greater than 0.5 mg/m^3.

In summary, for the comparison of offshore potential with production at the national level, whereas there were only 7 out of 15 mussel-producing nations and territories with offshore mussel potential based on all of the original criteria, by eliminating current speed as a criterion the number of nations and territories with offshore mussel potential increased to 13 (Table 13). In contrast, the effect of broadening the temperature and chlorophyll-*a* thresholds while retaining the current speed and depth criteria showed that ten nations had offshore potential (Table 13). With the broadened temperature and chlorophyll-*a* thresholds, but eliminating current speed as a criterion, all of the nations and territories currently producing the blue mussel were found to have offshore potential (Table 13).

TABLE 13
Blue mussel annual production by nation compared with offshore potential with areas meeting two temperature and two chlorophyll-*a* threshold ranges, as well as depth and current speed criteria, and areas meeting the first two criteria

No.	Nation or national territory	Mean annual production 2004–2008 (tonnes)	Potential (km^2) by temperature and chlorophyll-*a* threshold			
			Depth (25–100m) and current speed (10–100 cm/s)		Depth (25–100 m)	
			4 to 18 °C CHL >1 mg/m^3	2.5 to 19 °C CHL > 0.5 mg/m^3	4 to 18 °C CHL >1 mg/m^3	2.5 to 19 °C CHL > 0.5 mg/m^3
1	France	56 708	67	716	558	11 482
2	Netherlands	47 562	6	108	2 234	14 443
3	Ireland (Figure 49b)	36 751	0	0	1 454	30 405
4	United Kingdom	27 354	15	1 723	21 936	133 469
5	Canada	22 670	268	1 586	13 747	27 322
6	Germany	8 610	0	0	81	14 513
7	Norway (Figure 49a)	3 384	0	1 321	810	16 113
8	United States of America	2 017	379	1 158	15 846	60 570
9	Sweden	1 475	0	164	0	356
10	Denmark	686	0	2 596	2	14 781
11	Channel Islands	60	0	0	0	3 677
12	Argentina	30	5 247	8 208	20 215	177 072
13	Namibia	10	0	0	2 183	5 772
14	Iceland	6	0	24	133	4 049
15	United Kingdom (Falkland Islands [Malvinas])	6	77	0	206	7 646
Potential of nations or territories not yet producing blue mussel						
1	Chile	0	2 881	4 684	22 084	36 929
2	Australia	0	0	4 472	0	16 295
3	New Zealand	0	12	2 199	217	31 150
4	Belgium	0	0	0	249	1 217
5	South Africa	0	0	0	248	5 225
6	Spain	0	0	0	141	1 454
7	Denmark (Faroe Islands)	0	0	0	0	206
8	Denmark (Bornholm)	0	0	0	0	5
9	France (Crozet Islands)	0	0	0	0	418
10	France (Kerguelen Islands)	0	0	0	0	18
11	Portugal	0	0	0	0	2 130
12	United Kingdom (Tristan De Cunha)	0	0	0	0	10

5.3.2 National to local level offshore mariculture potential compared with inshore mariculture locations

This comparison was accomplished by mapping the locations of inshore mussel farms in western Ireland and the Kingdom of Norway together with the offshore areas meeting various combinations of thresholds (Figures 49a and 49b). In the Kingdom of Norway, mussel farms are found all along the coast, but are less abundant in the far north. Generally, the near offshore areas of the Kingdom of Norway in the vicinity of mussel farms meet up to three thresholds, while a small area in a segment of the coast (Figure 49a) meets all four thresholds. In this segment, much of the off-lying area meets temperature, chlorophyll-*a* and current speed thresholds, but the depth is not suitable for longlines. Closer to the off-lying islands in this segment, the temperature and chlorophyll-*a* thresholds are suitable, but one or the other, or both the depth and current speed thresholds, are not met. In Ireland, mussel farms are clustered in the south, central and northwest in much the same three areas where salmon farms are shown in Figure 48b. The Ireland comparison is hampered by the lack of current speed coverage close along much of the coast where mussel farms are located (Figure 49b). In the northwest further offshore, the depths are not suitable, but the other three thresholds are met. In contrast, in the west central area, three thresholds are met, but there the current speed is not suitable. This is also the case for offshore potential in the southernmost area of mussel farms.

5.4 IMTA offshore mariculture potential compared with inshore Atlantic salmon and mussel farm locations

No data on IMTA collectively for a country or at individual offshore locations were available for comparison or verification; however, Atlantic salmon and blue mussel are cultured at a number of experimental IMTA inshore sites in New Brunswick in eastern Canada, and both species are farmed in the same general inshore areas in the Kingdom of Norway (Figures 48a and 49a) and in western Ireland (Figures 48b and 49b) where offshore IMTA potential was found.

There is no potential for blue mussel-Atlantic salmon IMTA in non-mariculture countries because there is no potential for salmon there.

5.5 Summary of comparisons of offshore mariculture potential of cobia, Atlantic salmon, blue mussel and IMTA with inshore mariculture of these species

National-level offshore potential and national production comparisons

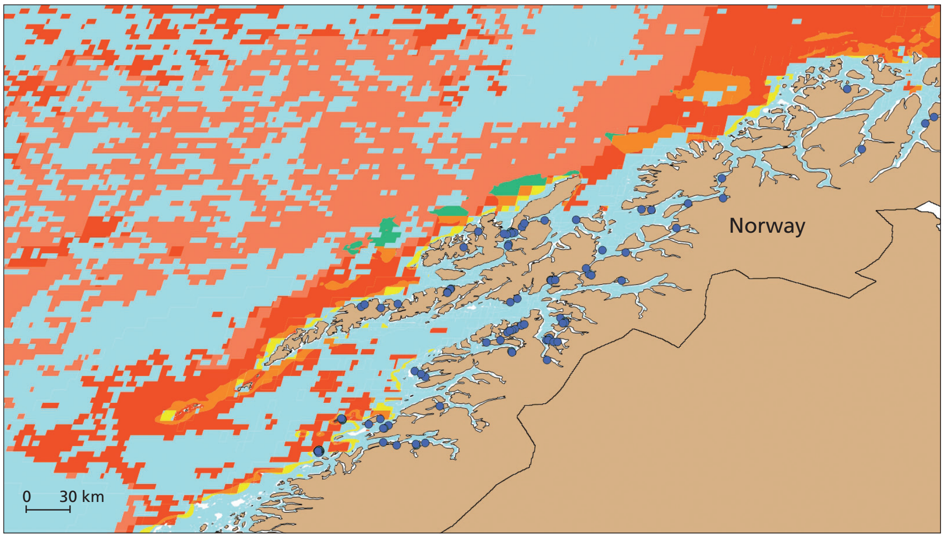
The rationale for a positive result from this comparison is simply that, where mariculture already exists in a country there is an advantage to its further development. Mariculture already in practice in a nation with the species used in this study is indicative of nationally established infrastructure, goods, services, juvenile production and other technologies as well as access to markets, which could be organized to support offshore development of these species.

Potential was found in all five of the nations reporting cobia culture. For the Atlantic salmon, there were 14 producer nations or territories, though production in three of them was very modest, ranging from 1 to 158 tonnes. With current speed removed as a criterion, potential was found in 12 of the 14 currently producing nations. Additionally, potential was found among six nations and territories not yet producing Atlantic salmon. For the blue mussel, there were 15 producer nations and territories, and potential was found among 10 of them. In similar fashion to Atlantic salmon, with current speed removed as a criterion, potential was found in the entire 15 nations and territories currently producing blue mussel. Additionally, potential was found among 12 nations and/or territories not yet producing blue mussel.

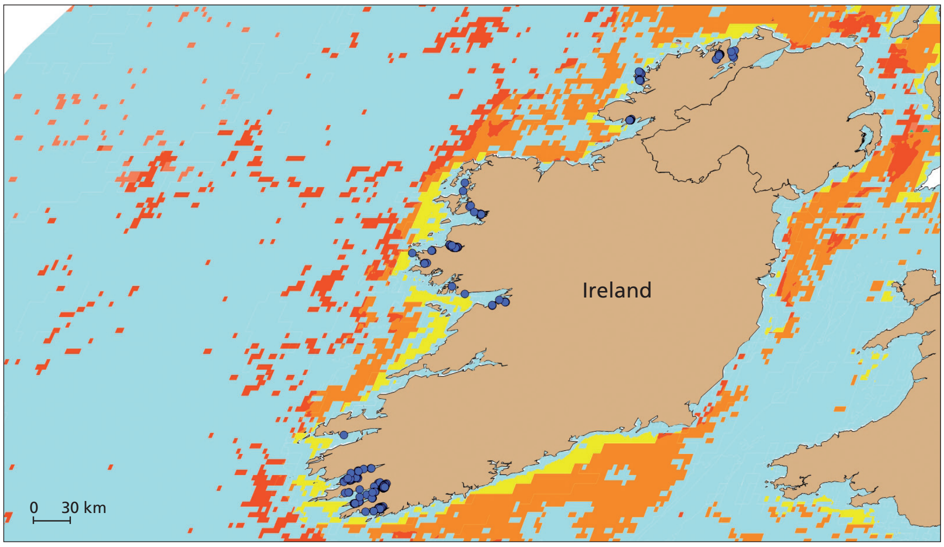
FIGURE 49a,b

Areas with temperatures and chlorophyll-a favourable for blue mussel grow-out and depths and current speeds suitable for longlines compared with locations of mussel farms in Norway and Ireland

a. Norway



b. Ireland



- Temperature, chlorophyll-*a*, depth and current speed suitable
- Temperature, chlorophyll-*a* and current speed suitable; depth not suitable
- Temperature, chlorophyll-*a* and depth suitable; current speed not suitable
- Temperature, chlorophyll-*a* and depth suitable; current speed no coverage
- Temperature and chlorophyll-*a* suitable; depth and current speed not suitable
- Temperature and/or chlorophyll-*a* not suitable; or no coverage
- Mussel farms

Offshore mariculture potential compared with inshore farm and farming area locations

The rationale for an advantage in the development of offshore mariculture in the areas where there is a correspondence between offshore potential and inshore practice is the same as for the national-level comparison above, but with all of the advantages of inshore practice being proximate to offshore areas with potential for development.

Cobia. For cobia, the locations of 22 cage sites and nine cobia farming areas among eight nations were examined for offshore potential. In all but 13 of the locations the temperatures were seasonally too cool to meet the 22 °C lower threshold limit, and evidence from literature reviews showed that these were farming areas with risk of relatively long grow-out durations or of mortalities caused by low temperatures. The cobia temperature threshold range was established to provide temperatures favourable for grow-out and thereby to be risk averse. Thus, the lower limit of the threshold (22°C) is justified.

Among seven farm locations or farming areas in six countries, all three thresholds were met relatively close offshore of five locations. Temperature and depth thresholds were met offshore of two other locations indicating good correspondence between inshore cobia farming and offshore potential where temperatures remain suitable year round.

Atlantic salmon. The comparison of offshore potential with locations of inshore farms included the Kingdom of Norway and the Republic of Chile, the two leading nations in Atlantic salmon production worldwide, as well as Canada and Ireland. Among these four nations, all three, or two, of the criteria were met offshore of the inshore farming areas. The comparisons for Atlantic salmon substantiate the estimates of offshore potential in that offshore potential has been identified in areas where inshore culture of this species is already practised.

Blue mussel. At the national level, offshore potential has been identified in areas in western Ireland, one of the most important blue-mussel-producing countries (Table 12). Offshore potential has been identified where inshore culture of this species is already practised. However, at best, three of four thresholds were met in western Ireland. In the Kingdom of Norway, all four thresholds were met along a small segment of the coast, and elsewhere up to three thresholds were met.

IMTA. No data on IMTA collectively for a country or at individual offshore locations were available for comparison or verification, but inshore blue mussel and Atlantic salmon farming does occur in close proximity in western Ireland and the Kingdom of Norway where there is offshore potential for IMTA, suggesting that offshore IMTA of blue mussel with Atlantic salmon could be considered.

Cobia offshore potential verification

Only four offshore farm locations were available for comparison with offshore potential. At one of these locations, all three thresholds were met; at another location, one farm site was adjacent to an area that met all three thresholds but the other met only one threshold, and at the last, temperature and depth thresholds were met, but there was no current speed coverage.

To summarize, these comparisons, despite being hampered in some instances by a lack of spatial data coverage in inshore areas, or of no current speed coverage, lend substantial credibility to the conclusion that, by the criteria of this study, there is much unrealized offshore potential for the three species and IMTA offshore of farming areas in nations where the culture of these species is already established.

6. Discussion and conclusions

6.1 Analytical approach

Overall, the analytical approach is flexible and expandable in that it can be readily modified to encompass new species and advances in culture practices individually or collectively, as well as take on improved or new data sets and additional criteria and constraints for development. Further, as demonstrated in this document, species and culture systems can be combined for IMTA.

An important question concerns the reliability of the estimates of offshore mariculture potential. In general, they are the result of a sequence of informed decisions based on the literature, contacts with mariculture experts, and on mariculture practice. The sequence of decisions began with the key assumptions about the near-future development of offshore mariculture (Box 2). The key assumptions set the stage for the identification of analytical criteria (Table 1). The analytical criteria then led to the choice of species and culture systems, and finally to the thresholds that were at the core of the spatial analysis (Table 1). Two key assumptions fundamentally shaped the spatial analyses: cages and longlines as the offshore culture systems, and fish and mussels with already proven culture technologies and established markets as the animals to be grown out offshore (Box 2). Clearly, the ranges within species and culture system thresholds substantially influenced the results. For this reason, each threshold was reported individually in order to illustrate its influence on the overall results. The effects of modifications of thresholds for the Atlantic salmon and blue mussel on offshore mariculture potential were made evident in Section 4.5. It is important to mention that the species-culture system thresholds are broadly indicative of offshore mariculture potential of the selected species as well as species with similar temperature and food availability thresholds, not predictions of offshore success of the selected species. For that, many more variables would have to be included in the assessment. Finally, the stepwise process emphasizes the importance of thorough literature reviews, contacts with experts, and information from mariculture practice in order to specify ranges that will identify areas that are favourable for offshore mariculture development.

Potential was identified in terms of locations, and quantified as surface areas meeting criteria in aggregate globally and for the 20 mariculture nations and non-mariculture nations ranking highest for the criteria. One measure of reliability is the original resolution of the data. As shown in Annex 1, Table A1.1 and presented in Annex 1, bathymetry is at a relatively high resolution of ~0.9 km, while temperature (~4.9 km), chlorophyll-*a* (~4.6 km) and current speed (~8.9 km) are at lesser resolutions. Thus, places where offshore potential has been identified are indicative of potential in the vicinity, not of pinpoint locations of potential. The estimates also are affected by the depths at which the original data were acquired. Temperature and chlorophyll-*a* are from the near surface owing to satellite-borne sensor limitations. In contrast, current speed estimates with global coverage were available at a minimum depth of 30 m, while the upper depth threshold for cages and longlines was set at 25 m. As a consequence, there are areas in the 25–30 m depth range that meet the cage and longline depth thresholds for which there is no current speed coverage. The result overall is that potential may be somewhat underestimated with regard to the effect of current speed. Variability in time is another consideration. Data were analysed on monthly time steps (Annex 1). In this regard, bathymetry is not likely to vary significantly with that time step. In contrast, temperature, chlorophyll-*a* and current speed are time variable. Current speed is likely to be the most variable in relation to the one-month time step of this study. In order to provide a statistical basis for the temperature, chlorophyll-*a* and current speed thresholds, 95 percent confidence intervals were generated around the mean values. An area would be considered to fall within a threshold if the full confidence interval around the observed value at that location was completely within the upper and lower threshold values (Annex 1).

An additional measure of reliability is the time span of records for the time-variable data. In this regard, temperature covered 17 years, current speed 5 years, and chlorophyll-*a* 7 years: however, chlorophyll-*a* was not available for five months in each hemisphere during the coolest time of the year. The result is that actual chlorophyll-*a* concentrations during the months without coverage may be less than the 0.5 mg/m^3 threshold. Yet another consideration is the amount of missing data within data streams because of the lack of coverage by satellite sensors. Despite this constraint, because the data were aggregated by the month based on daily capture, the probability is high for most locations to be well represented.

In spatial studies employing many criteria and constraints, it is the usual practice to place weights on the criteria in different categories to determine the relative importance for each criterion (e.g. Aguilar-Manjarrez and Nath, 1998; Nath *et al.*, 2000). In this technical paper, criteria were not weighted because each one of them is considered to be the *sine qua non* for offshore mariculture development. Improvements in the approach by modifying thresholds within criteria, another kind of weighting process, are discussed in Section 6.3.

6.2 Comparisons of offshore mariculture potential with inshore mariculture practice and verification

Estimates of offshore mariculture potential require verification in order to be credible and useful for development planning. As noted in Chapter 1, offshore mariculture is in its infancy, and, as a consequence, locations are scarce where offshore mariculture already is established for the three species in this study. Verification by comparing predicted offshore mariculture potential with actual offshore locations was possible only for cobia and at only four farm sites. Verification by comparing the natural geographic ranges of the three species with the areas predicted to have potential was considered. However, there are a number of problems. One is that the distribution maps themselves are not fully reliable. For example, the Center for Quantitative Fisheries Ecology maps the worldwide distribution of cobia in terms of relative likelihood of occurrence that can range from .01 to 1.00, indicating that in many instances the actual geographic range is uncertain (CQFE, 2012). Also, there may be a general problem with migratory fish. That is, an area that migrants occupy seasonally may not be suitable for their offshore culture throughout the year. In the case of the Atlantic salmon, there is another problem. Because of the introductions into new areas for culture (e.g. Australia, Pacific Canada, Republic of Chile), the natural range would not correspond to areas where potential was found outside of that range. In the case of the blue mussel, the exact range is not known because of the confusion with other very similar *Mytilus* (FAO, 2012). In fact, the blue mussel distribution map in the above-mentioned fact sheet shows its natural distribution in Ireland and in the Kingdom of Norway where offshore mariculture potential was found, but the same map does not show its distribution in the eastern Canadian provinces where it is cultivated nor in the adjacent northeastern states of the United States of America where it is also farmed to a small extent.

Other instances, where inshore mariculture was in close proximity to offshore mariculture potential, provided an indicative verification in the sense that offshore temperatures were similar to those experienced in inshore mariculture and that the offshore chlorophyll-*a* concentration threshold was met in areas offshore of inshore blue mussel culture. For Atlantic salmon and blue mussel, the causes of a lack of coincidence between the initial estimates of offshore potential and the locations of farming areas or farm sites in some regions were identified. Temperature and chlorophyll-*a* data were acquired from culture sites, and temperature and chlorophyll-*a* from nearby offshore areas were sampled from archived spatial data. With these data to hand, thresholds were modified to better reflect offshore mariculture potential. Once adjustments had been made to the thresholds, the predictive ability of the criteria for assessing mariculture potential was greatly improved.

The inshore-offshore comparisons lent considerable credibility to the estimates of potential for offshore mariculture development. A general conclusion was that, where inshore mariculture was already established, oftentimes there was offshore mariculture potential meeting all or nearly all of the criteria. In such cases, the presence of inshore mariculture would provide a development advantage for offshore mariculture in that technologies, goods and services and access to markets currently supporting inshore mariculture would already be available for extension to offshore mariculture development.

In conclusion, the verification and comparison exercises showed that, despite the limitations of the data, the results are sufficiently reliable for the objectives, namely to comprehensively and comparatively deliver locations and surface areas of offshore mariculture potential aggregated globally that are a first approximation of offshore mariculture potential at the national level. These estimates of offshore mariculture potential await the addition of many more criteria and spatial analyses at higher resolutions to be undertaken at a national level.

6.3 Improvements in the approach

Improvements in the approach could be made in two basic ways: one is through modifications of the analytical approach using the same spatial data sets that were employed herein, and the other way is by adding new criteria and new data sets. For the former, using shorter time steps for temperature is one improvement that could be made, with eight-day intervals as the next available time step in the archived data as compared with the one-month time steps used herein. Another innovation, either with the present one-month time step, or a shorter one, would be to identify the worst and best case sequences of temperature affecting grow-out based on the 17-year archive of SST data used in this study (Annex 1, Table A1.1). Using the current data set, it would be possible to create additional thresholds (additional classes within criteria) so that potential could be expressed in increasingly better levels of suitability. For example, temperature thresholds could be classified to indicate areas with increasingly improved prospects for rapid growth, and the cost-effective area could be further classified by distance from a port as was carried out by Kapetsky and Aguilar-Manjarrez (2007, 2010) for the eastern EEZ of the United States of America.

The approach also could be expanded by adding attributes to the spatial data sets used in this study. For example, depth thresholds could be created in relation to cage mooring installation and maintenance costs. The cost-effective area, which takes into account time-distance expenses for servicing offshore installations, could be varied from nation to nation by using fuel and labour costs as attributes. These attributes could then be used to modify the cost-effective area for development in relation to port locations.

The final way in which the approach could be improved would be to add criteria based on additional data sets that possess a global scope. One of these is wave climate. Attention was called to the calculation of the wave climate for offshore cage culture by Pérez, Telfer and Ross (2003). James and Slaski (2006) showed that wave climate is a prime consideration for cultivating fish offshore. The cage structure and nets undergo structural loads, wear and fatigue and, ultimately, failure. For the cultured fish, excessive wave action can cause physiological problems, reduced growth, physical damage and mortalities. In addition to the aspects mentioned above, wave height is important in several ways, including access by boat to and from offshore installations and for the physical security of personnel working on the boats and installations. Additionally, cages and longlines are submerged in order to establish a depth at which wave influences will not be harmful to fish and shellfish during storms. The depth of submergence is related to wave height that, in turn, influences installation and maintenance costs. Wave height, one of the aspects of wave climate, was considered as a criterion for the present study. The global monthly mean significant wave height (SWH) data based on satellite altimetry, mentioned by Queffeulou, Bentamy and Croizé-Fillon (2010), are at a 2 degree resolution (330 km at the equator) that is much coarser than the other data sets used in this technical paper (see Dean and Salim, Annex 3, Section 5.2). Mean monthly SWH with global coverage averaged for 2009 were provided by the IFREMER Laboratoire d'océanographie spatiale (P. Queffeulou personal communication, 2012) with the caveats of complications from sampling and spatial variability of wave height. A preliminary analysis showed that, as a consequence of the coarseness, there was mean 2009 SWH coverage of only 73 percent of the global EEZ area. The same SWH data set covered 72 percent of the area with temperatures suitable for Atlantic salmon and depths and current speeds suitable for cages. In comparison, the SWH coverage was 60 percent of the area with temperatures suitable for cobia and depths and current speeds suitable for cages. Nevertheless, the potential usefulness of SWH data for assessing offshore mariculture potential was shown by a comparison of SWH ranges between the areas with potential for Atlantic salmon and cobia (Table 14).

TABLE 14

Mean SWH ranges in 2009 in areas suitable for offshore mariculture of Atlantic salmon and cobia

Mean SWH range in 2009 (m)		< 1	1–2	2–3	3–4	4–5
Atlantic salmon	Area (km^2) in the range	0	157	8 434	9 903	3 475
	Percent of area in the range	0	1	38	45	16
Cobia	Area (km^2) in the range	44 140	395 999	29 495	0	0
	Percent of area in the range	9	84	6	0	0

These results, although quite limited by spatial and temporal coverage, suggest that average annual SWH is several metres higher in areas suitable for salmon than in areas suitable for cobia, with multiple implications for culture structures and cultured fishes between the two kinds of offshore mariculture development. Other wave climate measures have been created in the KNMI/ERA-40 Wave Atlas (Caires, *et al.*, 2004) that is a climatology of wave climate including SWH and wave period the latter an important parameter for offshore culture structures. The estimates are based on data averaged on a 1.5°x1.5° area and the ocean wave data are only valid in deep water regions. Nevertheless, these wave-climate measures should be pursued in future studies.

Global data sets could be useful in several ways as extensions of the present study. One way is to place offshore mariculture in the broad context of status of oceans. The Global Ocean Health Index provides a vehicle by measuring the ocean's overall condition within the EEZ of each country on the basis of ten goals and with accompanying data layers (Halpern *et al.*, 2012). Another global data set that could be used to illustrate competing and conflicting uses, as well as to indicate water quality is described by Halpern *et al.* (2008) as part of the multicriteria Global Map of Human

Impact on Marine Ecosystems. The most relevant individual digital maps described by Halpern *et al.* (2008) are shipping activity and ocean pollution at nominal resolutions of 1 km^2. Another useful global data set, this one in tune with the ecosystem approach to aquaculture (EAA) development, is the Global 200 data set of Olson and Dinnerstein (2002). The Global 200 are the ecoregions that harbour exceptional biodiversity, of which there are 43 marine priority regions as well as terrestrial and freshwater ecoregions. The importance of these ecoregions in relation to aquaculture was summarized by Kapetsky, Aguilar-Manjarrez and Soto (2010). The Global 200 ecoregions were used by Kapetsky and Aguilar-Manjarrez (2008) as an example of the loss of potential for offshore culture of cobia by excluding areas suitable for cobia from the Global 200 marine ecoregions. About one-third of the global area with potential for good growth of cobia in sea cages at 25–100 m depths would be lost by using the marine Global 200 ecoregions of the world as a constraint.

The potential impact of climate change on aquaculture was assessed by De Silva and Soto (2009). In the marine realm, the potential impact of climate change on offshore mariculture could be investigated mainly through forecasting changes in locations and quantities of areas with offshore mariculture potential in relation to changing ocean temperature, ocean chemistry and primary production, and locational shifts in storm events.

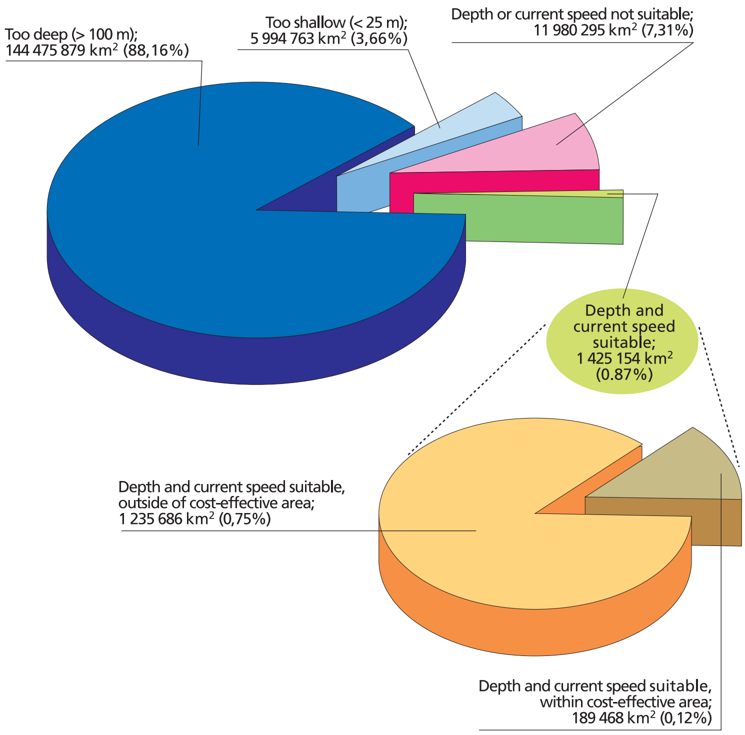
6.4 Offshore mariculture potential

This study is based on the technical requirements of culture systems that will be important in the near-future development of offshore mariculture as well as on several representative species generally indicative of finfish and mussel offshore potential. The study shows that basic criteria can be used for a spatially quantitative view of indicative actual and near- future offshore mariculture potential at global and national levels. One of the major benefits of this study is that it provides, for the first time, estimates of the status and potential of offshore mariculture that are comprehensive of all maritime nations and comparable among them.

The results of this study indicate large, unrealized offshore mariculture potential from a spatial perspective. There are several lines of supporting evidence in this regard. The first line of evidence comes from the present status of mariculture (Chapter 2). The results pertain mainly to inshore mariculture. These results show that, in all, 93 countries and territories practised mariculture during the period 2004–2008, and that there were 72 maritime countries and territories (44 percent of the total) that were not yet practising it. Those already practising mainly inshore mariculture are doing so with highly varying intensities of production, ranging from a fraction of a tonne per kilometre of shoreline to more than 500 tonnes per kilometre of shoreline (Figure 4). One-half of those nations or territories are producing at less than 1 tonne per kilometre of coastline, suggesting that mariculture could be expanded in many countries.

A second line of supporting evidence also indicates large offshore mariculture potential in absolute terms. The evidence comes from the results of the spatial analysis of the basic technical and economic criteria upon which offshore development must depend (i.e. depths and current speeds for cages and longlines and cost-effective area for development) (Section 4.4). These criteria, in broad terms, represent the present limits of offshore technologies and offshore operational reach in cost-distance terms. The overall situation is summarized in Figure 50. Assuming that global offshore mariculture potential is represented by the aggregate global area within EEZs, there would be nearly 164 million km^2 available for development, with all other uses set aside. However, in relative terms, near-future offshore mariculture is severely limited by the need to tether cages and longlines to the seafloor in that about 92 percent of the EEZ area is either currently too deep or too shallow for cages and longlines. In 7 percent of the EEZ area, either depth or current speed is suitable, but there is no spatial overlap

FIGURE 50
Areas (km²) within EEZs relative to depths and current speeds suitable for sea cages and longlines and to the cost-effective area for development



between the two criteria. The area with both depth and current speed suitable beyond the cost-effective area for development represents only about 0.9 percent of the total EEZ area. However, this area is quite large in absolute terms, about 1.4 million km^2. With the cost-effective area for development taken into account together with suitable current speed and depth, the area suitable for development in technical and cost-effective distance terms is about 0.1 percent of the total EEZ area, but this, too, is absolutely large, nearly 190 000 km^2. This measure corresponds to the offshore potential to be realized beginning in the immediate future and extending for years to come while taking into account that offshore installations are bound to shore-based services. Given that the cost-effective area employed in this study is only broadly indicative of the economic limiting distance for offshore development, this still represents a vast area within reach of present technologies with all other uses and other limiting criteria set aside. As autonomy and other technologies are improved, this area will expand seaward.

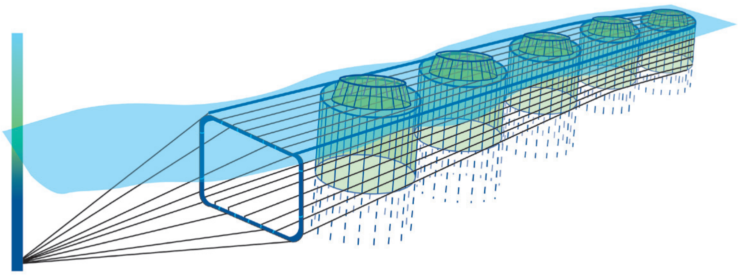
Improvements in mooring systems could further expand offshore mariculture potential. Goudey *et al.* (2001) note that a single-point mooring (Figure 51) could reduce the anchoring costs of a cage operation by 50 percent compared with the then current multianchor methods.

Single-point mooring cost reduction is due to reduced hardware installation and maintenance costs. Assuming that the cost savings of the single-point mooring of sea cages would result in technical and economic feasibility for up to 150 m compared with the 100 m limit used in this study, then the additional area with potential would expand by 4.2 million km^2, current speed limitations set aside. This is a considerable increase, 31 percent, over the 13.4 million km^2 area in the 25–100 m depth range.

Yet another view of unrealized offshore mariculture potential relates to divorcing offshore installations from their present dependence on being moored. Free-floating and propelled installations represent offshore mariculture potential for the future. Although there is a relatively small proportion of the global EEZ area that is within the present depth limits of moored cages and longlines, there is a vast area with potential for mariculture using free-floating and propelled installations as envisioned by Wilcox (1982), Loverich and Goudey (1996), Goudey (1998a and 1998b), and Goudey *et al.* (2001). Recently, the Velella Project tested an untethered, free-floating Aquapod net pen culturing kampachi (*Seriola rivoliana*) in the waters offshore from the Big Island of Hawaii (Plate 6). The Velella Project ranged from 3–75 nm (5.5–138.9 km) offshore, in waters up to 4 000 m deep, with a combination of passive drift and towing from a steel-hulled schooner, which acted as the tender vessel, dive platform and feed barge (Sims and Key, 2012).

As noted by Loverich and Goudey (op. cit.), the Ocean Drifter would drift with ocean and coastal currents, but have the capability for self-propulsion. The conceptual design of Goudey *et al.* (2001) has a normal draft of 45 m. Allowing a 5-m margin for safety, the space available for such an installation, globally aggregated within EEZs, amounts to about 153 million km^2. Another similar design of the Ocean Drifter is pictured by Ryan (2004), that one with a 24-m draft (Figure 52). Taking 25 m as the minimum depth for that version, the area available would be nearly 158 million km^2. The areas most suitable for Ocean Drifters would be those that experience reciprocal tidal currents or gyres in order to maintain ideal conditions for growth (Loverich and Goudey, op. cit.). Placement within predictable ocean currents constitutes another possibility for mobile cages (Goudey, 2009). This requirement could greatly limit the area that is actually suitable for free-floating and propelled cages, as compared with the vast area potentially available within the EEZs mentioned above.

FIGURE 51
Idealized diagram of a multiple sea cage system with a single point mooring

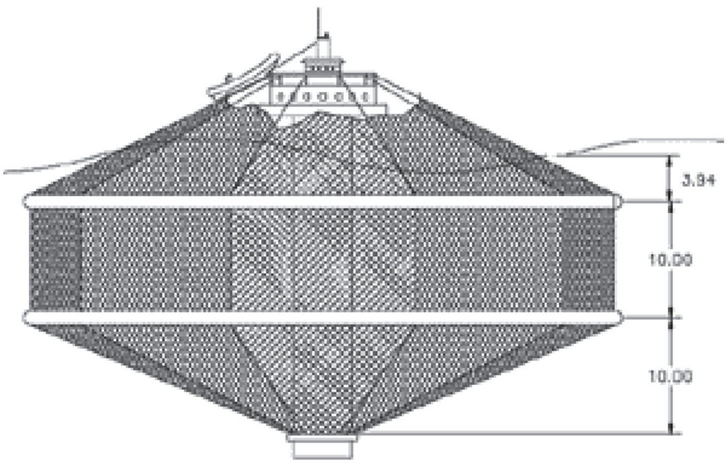


Source: SUBFlex (2011).

PLATE 6
Experimental version of an offshore towed fish cage

COURTESY OF N. SIMS

FIGURE 52
An Ocean Drifter cage concept

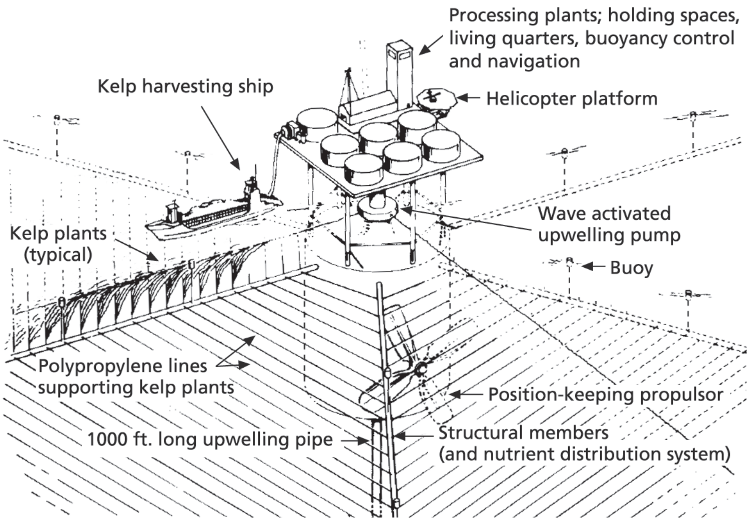


Source: Ryan (2004).

Another kind of ocean farming system was envisioned by Wilcox (1982). This was an untethered powered structure for kelp farming ultimately providing food for human consumption as well as industrial products (Figure 53). The concept is based on nutrient-rich waters pumped up from depths of from 100–300 m with fish and oyster farming also undertaken. A siting criterion was in consideration of latitudes with the least storms. In a techno-economic feasibility analysis of offshore seaweed farming for bioenergy and biobased products, Roesijadi *et al.* (2008) envisioned a 1 km^2 offshore seaweed farm that would be dynamically positioned both vertically and horizontally, with the latter maintaining the system in waters with sufficient nutrients and the former providing protection from storms. For Ocean Drifter and other mobile open ocean farms, a possible limiting factor could be special legal and commercial agreements among nations (Wilcox, 1982) covering not only revenue for use of ocean space, but also animal health, invasive species and the like if the mobile installations traverse EEZ boundaries.

Thus far, the discussion has dealt only with offshore potential with respect to technical and cost-distance limitations. It now turns to a final line of supporting evidence for large offshore mariculture potential that is based on the results of integrating fish and mussel growth-temperature thresholds with technical and cost-effective area for development criteria. The results of this integration indicate that there is much potential for species with grow-out temperature and current speed thresholds similar to those of the three species used in this study. Offshore potential remains large for species like these in absolute terms, both in area and in number of nations that could be participants in its realization even when the cost-effective limit of suitable areas within 25 nm (46.3 km) of a port is imposed (Figures 45 and 46). However, offshore potential is much greater in tropical and warm temperate waters than in cool and cold temperate areas, as indicated by the results for cobia. In contrast to the cobia, the offshore mariculture potential for Atlantic salmon and blue mussel is essentially limited to the nations already culturing these species inshore; however, even though the areas with potential are small in comparison with the cobia, the absolute amounts of area offer much opportunity for expansion offshore (Figures 45 and 46). The apparent advantage of tropical and subtropical waters for the development of offshore mariculture is due not only to temperatures favouring grow-out but also to larger areas meeting technical and cost-effective distance criteria. Olsen *et al.* (forthcoming) showed that the Intertropical Convergence Zone (ITCZ) ranked first area-wise in depths suitable for cages and longlines and for current speed when considered individually and when integrated. In cost-effective area for offshore development, the Northern Temperate Zone ranked first and ITCZ ranked second among mariculture nations, but among non-mariculture nations, the ITCZ ranked first. Finally, when depth, current speed and cost-effective area criteria were integrated, the ITCZ ranked first both among mariculture and non-mariculture nations alike.

FIGURE 53
Conceptual design of a 400-ha ocean food and energy farm unit



Source: Wilcox (1982).

Indicative offshore mariculture potential in terms of surface area for representative fish and a mussel has been shown to be large. A fundamental question is, How much area is sufficient for offshore mariculture development that would contribute to the global food supply? Kapetsky and Aguilar-Manjarrez (2010) used their estimates of area-wise potential for Atlantic salmon and blue mussel in the eastern EEZs of the United States of America, along with production per unit area data for large submersible sea cages (9 900 tonnes/km^2) and mussel longlines (4 000 tonnes/km^2) tabulated by Nash (2004), to estimate total production if only a fraction of the area with potential were to be utilized for offshore mariculture. The same approach is used herein. It is based on the global area with offshore potential for cobia, Atlantic salmon and blue mussel, including meeting the temperature thresholds, cage and longline depths and current speeds, and within the cost-effective area for development. Scenarios of 5 and 1 percent of the area suitable for development for offshore mariculture for each species are set out in Table 15. The extrapolated results are that with the 5 percent development scenario about 49 million tonnes of fish could be produced and about 1.1 million tonnes of mussels. With the 1 percent development scenario, the corresponding production is nearly 10 million tonnes of fish and 230 000 tonnes of mussels (Table 15). In comparison, the mariculture production of fish in 2010 was about 3.3 million tonnes and about 1.8 million tonnes of mussels The amount of space that was allowed to satisfy carrying capacity requirements is not clear from Nash's (op. cit.) tabulations, but space for operational access was included. Harvest in the second year was foreseen. Thus, with grow-out periods of more than one year the actual area required could be somewhat larger to produce the amounts shown on an annual basis in Table 15 especially for Atlantic salmon because of its longer grow-out period compared to the other two species. Nevertheless, an important point made by Nash (2004), and also evident from the results herein, is that production from relatively small areas can have a substantial impact on overall mariculture production.

TABLE 15
Extrapolated annual production from the aggregate areas suitable for the offshore mariculture of cobia, Atlantic salmon and blue mussel with 5 percent and 1 percent of the areas developed for offshore mariculture

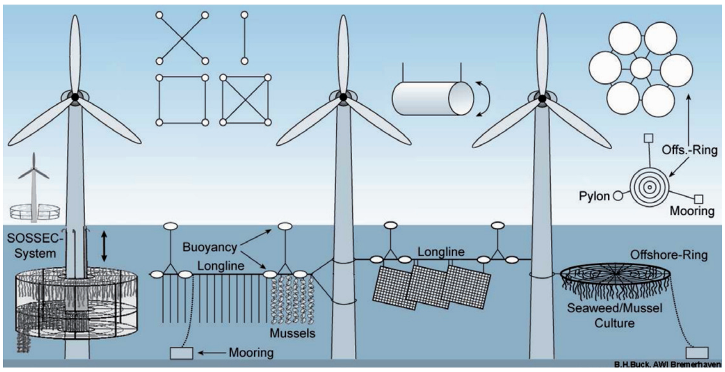
Species	Assumed production rate* (tonnes/km^2)	Total area suitable for development (km^2)	5% developed		1% developed	
			Area (km^2)	Production (tonnes)	Area (km^2)	Production (tonnes)
Cobia	9 900	97 192	4 860	48 110 040	972	9 622 008
Atlantic salmon	9 900	2 447	122	1 211 265	24	242 253
Blue mussel	4 000	5 848	292	1 169 600	58	233 920
Total		**105 487**	**5 274**	**50 490 905**	**1 055**	**10 098 181**

**Nash (2004).*

As a comparison of outputs, Wilcox (1982) foresaw an annual production of 700 000–800 000 tonnes wet weight of seaweeds per square kilometre on ocean farm structures based on artificial upwelling, and that would also include fish and oyster outputs (Figure 53). Forster (2011b; forthcoming) notes that while extrapolations can be pushed too far, based on the kelp (*Laminaria*) production being realized in the People's Republic of China, 1 940 tonnes dry weight/km^2 (Chen *et al.*, 2007), it would need less than 1 percent of the Earth's ocean surface, about 3.1 million km^2, to grow an amount of seaweed equal to all the food plants farmed on land.

Basic kinds of offshore mariculture potential have been identified in this study, including technical, economic and growth of cultured organisms. An important question going beyond the area required for development is the time frame in which offshore potential can be realized. As noted above, the offshore potential that could begin to be tapped in the near future is best described by that identified within the cost-effective area of development as a first approximation. For as long as offshore installations require frequent visits for maintenance, monitoring and harvest, they will have to remain proximate to onshore service installations located in industrial ports or in lesser harbours. Taking advantage of structures established for other uses of marine space, such as oil and gas platforms and wind farms (Figure 54), could accelerate offshore mariculture development by cost-sharing (e.g. shared transportation), as well as allowing mariculture systems to populate areas further offshore by making structures and services multifunctional (Buck, 2011). This would allow some of the present onshore services required of mariculture to be moved offshore (feed warehouses, lodging for maintenance and monitoring staff). One example of a synergistic relationship is shellfish harvesting as a biofouling control on platforms in the Santa Barbara Channel, California, United States of America (Richards, Culver and Fusaro, 2009). There, biofouling was a costly stress-load problem on platform legs and crossbeams that was reduced or eliminated by commercial harvest by shellfish entrepreneurs. One important factor was favourable conditions for the rapid growth of mussels, *Mytilus galloprovincialis* and *M. californianus.* From the viewpoint of sustaining bivalve culture at offshore wind-farm sites, Linley *et al.* (2007) predict with reasonable confidence that blue mussels could grow well at 15 wind-farm locations in three areas of the coasts of England and Wales. According to Brenner (2009) with regard to macroparasites, growth and aesthetical appearance *M. edulis* of high quality can be produced offshore in the German Bight.

FIGURE 54
Offshore wind farm combined with oyster and mussel farming



Source: Buck (2011).

Up to this point, vast offshore mariculture potential has been assumed with other uses of marine space set aside. However, MPAs are an illustration of possible competing, conflicting or complementary uses (Section 4.4) and a reminder that, although the area-wise and nation-wise potential indicated by the results is large, that potential will be reduced considerably by alternative uses for the same marine space, especially in nearshore areas where current marine activities are focused. For an example, in the current study, a hypothetical loss of cobia offshore mariculture potential amounting to about 6 percent in order to avoid MPAs was illustrated. As comparison at the subnational level, reduction in area with offshore mariculture potential when multiple constraints are considered comes from the Gulf of Mexico Aquaculture Fishery Management Plan. One of the alternatives of the plan would establish 13 marine aquaculture zones for fish in cages, amounting to about 5 percent of the Gulf of Mexico EEZ area of the United States of America (Gulf of Mexico Fishery Management Council and National Marine Fisheries Service, 2009; Rester, 2009). The aquaculture zones were defined by depths of 25 to 100 m and current speeds > 10 cm/s. Areas not considered suitable for aquaculture included navigational fairways, lightering zones, oil platform safety zones, permitted artificial reef areas, Habitat Areas of Particular Concern, coral areas, marine reserves, MPAs, areas of high shrimp fishing effort, and hypoxic areas (< 2 mg/l). Consideration of all of these constraints reduced the original area deemed suitable to 36 percent of the original total.

In summary, there are many other uses for ocean space that will affect offshore mariculture potential of which some are possibly conflicting and competing activities, as illustrated by the Gulf of Mexico study above, or potentially complementary (e.g. wind-power installations). An important goal of spatial analysis is to locate and quantify the complementary uses while avoiding or minimizing the competing and conflicting uses (FAO/Regional Commission for Fisheries, 2011). In this regard, this study, in a very broad way, serves to establish the spatial domains that could become offshore mariculture uses as a component in marine spatial planning.

6.5 Future directions

Taking into account the trend for the increased kinds and higher resolutions of environmental variables important for offshore mariculture development as well as improved computing power, it is likely that a grid-cell based model would be better suited to estimating offshore mariculture potential than raster-vector combination used for this technical paper. In this regard, the first step has been taken towards such an alternative approach to estimating mariculture potential that eventually could become a spatially comprehensive grid-cell based model to estimate mariculture development potential at individual locations of relatively small size (see Ferreira, 2013 in Annex 2). Attention was called by Kapetsky and Aguilar-Manjarrez (2013) to the need for applications that include carrying capacity as one of their components or outputs. Applications are needed that incorporate multiple models (e.g. economics, environment, social outcomes), multiple species, and the possibility that they could be scaled up to contribute to geographically broad studies at national levels as a part of a process of estimating aquaculture potential. AkvaVis (Ervik *et al.*, 2008, forthcoming; described by Ferreira *et al.*, 2012) is an "all-in-one" Web-based interactive decision-support system, including site selection, carrying capacity and management monitoring modules, that appears to have much promise for adaptation to estimating offshore mariculture potential at national levels and for the management of its development.

Data from satellite remote sensing were indispensable for the analyses carried out in this study, and will be important for the integration of spatial analyses and modelling referred to above. As stated by Dean and Salim (Annex 3), satellites enable a unique synoptic view of the seas and oceans and regular repeated observations of the entire globe and specific regions that complement and extend data available from operational meteorological and in situ sensors.[6] Operational oceanography data and information products derived wholly or partly from remote sensing include temperature, primary productivity, ocean winds, currents and waves. An important application of such data in real-time is for operational management of mariculture. In contrast to data for real-time management, the build-up of long-time series of data and advances in data processing mean that series of daily, weekly, monthly, annual and seasonal "climatology" data are now readily available at increasingly higher resolutions. In turn, these data improvements will enable more reliable estimates of mariculture potential at all levels while cutting costs. In addition, emerging remote sensing capabilities, such as more reliable identification and tracking of harmful algal blooms, will provide improved spatial and temporal risk assessment. This will complement the methodological approaches developed herein that are meant to stimulate estimates of mariculture potential at regional, national and subnational levels.

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[6] Remote sensing and its integration with GIS to enable spatial analyses for aquaculture and fisheries is covered by Dean and Populus (2013).

6.6 Recommendations

As FAO moves towards guiding the development of offshore mariculture through its regional fishery bodies and via technical assistance at national levels, assessments will have to be undertaken to determine the regions and countries that are most promising for development. Also, decisions will have to be taken on the appropriate technical interventions required to sustain mariculture. National-level assessments could be undertaken at several levels. For example, the results of this study show that a significant number of maritime nations are not yet practising mariculture, let alone offshore mariculture (Chapter 2). This suggests the need for a proactive approach by FAO and interested maritime nations not yet practising mariculture that would be a broad-based but rapid appraisal as a desk study to determine the reasons for the lack of mariculture development. From a spatial point of view, this technical paper provides one of the inputs by identifying the non-mariculture nations ranking highly in offshore mariculture potential. Other inputs could be taken from the Ocean Health Index (Halpern *et al.*, 2012) already described in Chapter 6.3.

Nations already practising mariculture, but at relatively low intensities, would require more detailed appraisals of their potential for the development of offshore mariculture. One of the recommendations of the FAO workshop report on offshore mariculture (Lovatelli, Aguilar-Manjarrez and Soto, forthcoming) is for GIS-based feasibility studies to be conducted on mariculture potential at the national level, including appropriate logistics and infrastructure. In fact, spatial analyses should be included at each stage in this process as an indispensable element of policy and planning in order to provide for a quantitative, comprehensive and comparable view of potential. The manner of organization of the spatial analyses supporting estimates of offshore mariculture potential is important in order to attain the most reliable outcome with the least cost.

A holistic project approach is needed based on an interdisciplinary team that plans the study using the principles of the FAO Code of Conduct for Responsible Fisheries (FAO, 1995; FAO Fisheries Department, 1997) and the EAA (FAO, 2010) as a starting point and with attention to the role of spatial planning tools to contribute to the realization of the EAA (Aguilar-Manjarrez, Kapetsky and Soto, 2010). The project could be placed in a government agency and/or executed by a consulting firm. An important stipulation is that the team should identify its information needs for each discipline at the beginning, and integrate its expertise in an interdisciplinary way thereafter. At the least, the core team should consist of a mariculture expert with a broad knowledge of species and culture systems, an aquaculture economist (modelling), an environmental expert (carrying capacity modelling), a sociologist (societal costs and benefits), and a GIS expert with experience in mariculture, marine fisheries or marine ecosystems. Built into the project should be funds to access additional expertise as required (e.g. marine aquaculture engineers, oceanographers, mariculture practitioners, mariculture entrepreneurs, marine legal experts). Most important is the contact with the mariculture industry in order to ensure that the design of the study is shaped realistically and so that the predictions of potential can be verified with experience from mariculture practice. The team has to be outward looking in order to obtain information and advice from the commercial sector, university researchers, government agencies, and from other potential users and conservers of marine space. Regarding government agencies, it is worthwhile to note that for the foreseeable future offshore mariculture has to be shore based. Thus, local governments and the many stakeholders they represent are important participants in planning for offshore mariculture development. An example of a national-level desk-based appraisal of the opportunity for offshore aquaculture is provided by James and Slaski (2006), but spatial analyses appear to have contributed little to the process. In contrast, an atlas of suitable sites for mariculture projects has been produced by the Sultanate of Oman (Ministry of Fisheries Wealth, 2010) that is based on remote sensing and spatial analysis, but would be considered as a companion piece to a more broad-based study of mariculture potential.

Viewed from a commercial and entrepreneurial standpoint, the results of such analyses can go a long way towards stimulating interest and confidence in offshore mariculture development. The utility and value of estimates of mariculture potential can be increased and the results improved in a number of ways, including by expanding the number of animal species and by adding marine plants and their culture systems, by increasing the numbers of criteria and the resolution of the data, and by applying a model-based approach. All of these refinements can be achieved at a relatively modest cost. Given the experiences gained in this study, efforts should be made to refine the process and to technically assist countries to implement their own estimates of mariculture potential. Based on the result that most of the offshore fish farming potential is in the ITCZ, it can be inferred that many of the nations are in the "developing" category and may require technical assistance. Funding for both of these activities should be included in the broader effort to expand mariculture to offshore.

Looking more broadly, there is a pressing need to identify areas that can help to satisfy the food needs of the increasing world population. Forster (2007) points out that if the oceans are to be farmed like the land, then the offshore areas must be farmed for plants that will provide human food as well as industrial products. This indicates assessing the potential for farming marine macrophytes (seaweeds) on floating structures, or locating or creating conditions for floating seaweeds (Forster op. cit.). This need is being satisfied by a global review currently under way by FAO on seaweed aquaculture, developmental constraints and opportunities. Spatial analysis can be applied to the "What?", "Where?" and "How much?" of offshore seaweed farming potential much in the same way as for the finfish and mussel analysis of this technical paper once environmental, technical and economic thresholds have been established. The results of the seaweed study should then be integrated with those for finfish and shellfish in order to reveal opportunities for IMTA.

Going along with the need to predict offshore mariculture potential is another need that was identified by Knapp (forthcoming). That need is to monitor the growth of the offshore mariculture industry. For this purpose, FAO and Member countries will need to create a new aquaculture statistical category "offshore mariculture". Underlying this initiative is the need for a simple, spatially oriented but unambiguous concept of offshore mariculture. In this regard, and most simply, offshore mariculture from a spatial perspective is defined by where offshore mariculture is presently being practised, by the species that are being cultured, by the culture systems employed, and by the condition of the surrounding environments. The surrounding environments include the biophysical, social and economic environments along with their administrative contexts. Thus, offshore mariculture, present or future, can be defined spatially on maps by the offshore and onshore locations of installations with their attributes catalogued in spatial databases. The combination of the spatial data and attribute information when categorized by administrative, social, economic and ecological criteria could be integrated into an offshore mariculture development and management- information type system. Such an information system would have many applications within the realm of aquaculture (promotion, policy and planning, regulation). More broadly, it would place mariculture in the context of more general development and management of ocean space within marine spatial planning initiatives, such as set out by the FAO/Regional Commission for Fisheries (2011) and in atlas form by Suárez de Vivero (2011).

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Annex 1

Overview of the spatial analyses and data sources

This annex briefly describes the processing steps used to create the results of the spatial analyses presented in this technical paper.

1. Hardware and software

The GIS software used in this study was Manifold (CDA International Ltd.) and ArcGIS 9.3 (ESRI). Manifold, versions up to 8.0.27, was used because it is a very affordable (currently about one-fifth of the cost of the most widely used GIS software) but fully functional GIS. ArcGIS 9.3 was used to prepare the raw data and to perform more complex analysis.

The text below describes the conceptual steps necessary to replicate the analysis described in this technical paper. Readers should be aware that most of the ArcGIS analysis could not be done with the standard ArcGIS tools, and, therefore, required custom VBA (Visual Basic for Applications) functions (i.e. codes) were required to conduct the analysis. The VBA computer codes written for this technical paper are available upon request from the authors of this technical paper, but they will only be useful to readers using ArcGIS with VBA installed and licensed.

2. Spatial data

Spatial data used for this technical paper were: (i) exclusive economic zones (EEZ); (ii) bathymetry; (iii) current speeds; (iv) world ports; (v) sea surface temperature (SST); (vi) chlorophyll-*a*; (vii) marine protected areas; (viii) Global Administrative Area from the GADM database; and (ix) geographic zones (see Table A1.1 for details).

All data sets used in this study are presented in Section 4 of this Annex and are available for download in FAO's GeoNetwork portal (www.fao.org/geonetwork).

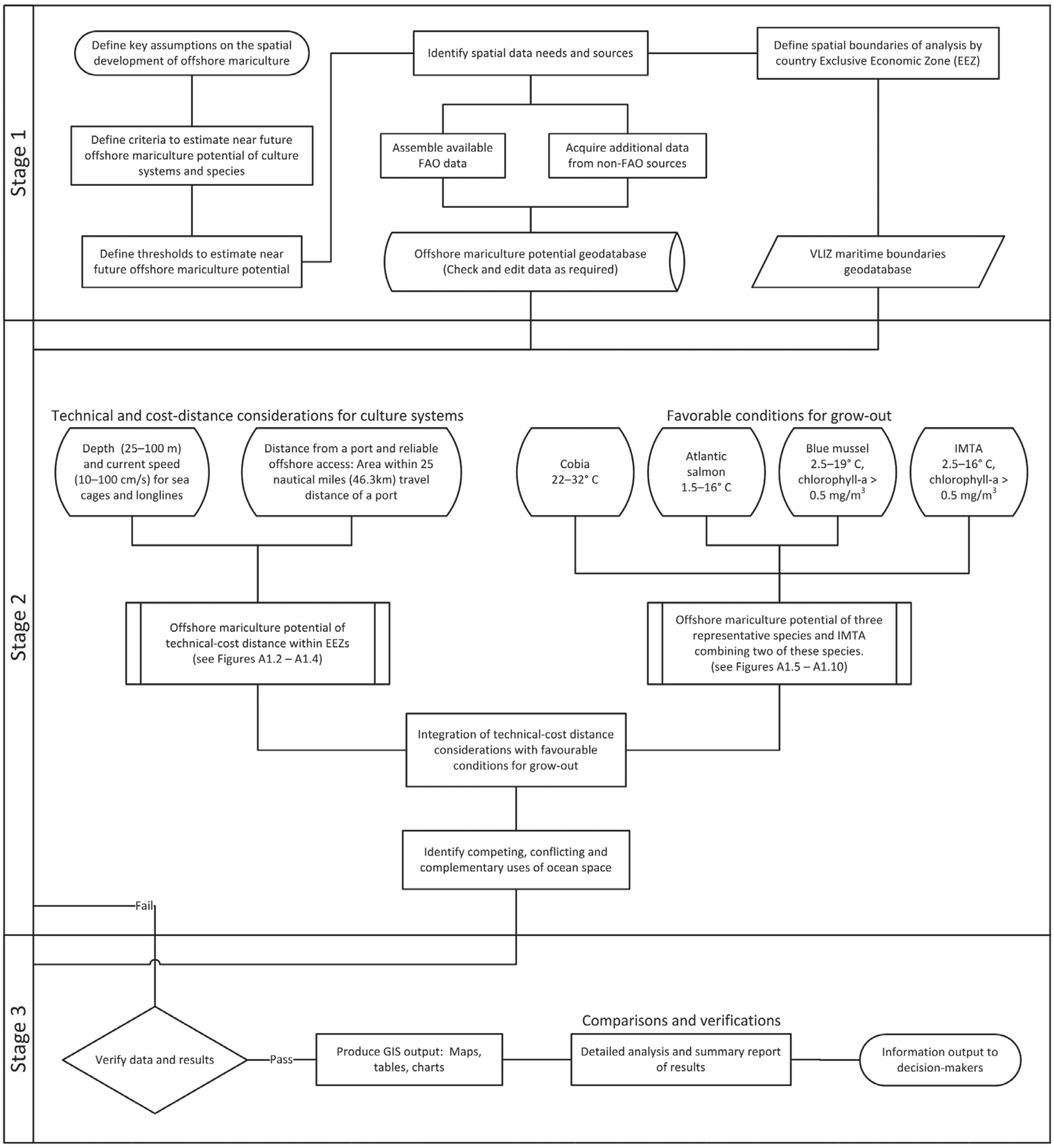
3. Spatial analysis

This study identifies areas that satisfy criteria for offshore mariculture development. The criteria include the suitability of depth and current speed for sea cages and longlines, and the temperatures favouring grow-out of representative species: cobia (*Rachycentron canadum*), Atlantic salmon (*Salmo salar*) and blue mussel (*Mytilus edulis*), as well as chlorophyll-*a* concentration for the last species.

There were two important limitations to this study. First, only already-digitized or computer-ready data could be used for the analysis to save costs, and second, because offshore mariculture potential is being predicted for areas where it largely does not yet exist, verification was limited to using the location of a few offshore fish farms and relied mainly on comparisons of offshore potential with existing inshore mariculture. Another limitation was that the data had to be comparable for all maritime countries. In overview, this study consisted of three major analytical stages (Figure A1.1):

(i) data preparation;
(ii) integration of data sets; and
(iii) verification.

FIGURE A1.1
Major analytical stages



Note: Fail acknowledges that verification could be incomplete, or in some cases fail.

Note: Areas with potential within EEZs, but presently outside of cost-effective areas for development were estimated by setting aside the cost-effective area for development (see Table 1, Criterion 4).

3.1 Data preparation

Various aspects of this analysis required analysing and processing data in both raster and vector formats. The general strategy with raster data was to do all analysis at the finest resolution of the data, and then to convert the final to vector format for further analysis. For example, if a particular analysis was required to identify regions that met thresholds using multiple rasters, then the new raster that was generated would have the same resolution as the finest resolution of the multiple input rasters. The new raster would then be converted to a polygon feature class[7] for further analysis.

[7] A polygon feature class is a geographic data set of polygonal vector objects (i.e. entities that cover an area, such as administrative units or analysis areas), plus associated attribute information for each polygon. Other examples of vector data sets include polyline feature classes (containing linear features such as roads or rivers) and point feature classes (containing such things as port locations).

EEZ boundaries to define the spatial limits for near-future offshore development

Exclusive economic zone boundaries were taken from the Flanders Marine Institute (Vlaams Instituut voor de Zee, or VLIZ) data, Version 5.

Depth and current speed to define the spatial limits on offshore cages and longlines

Regions suitable for offshore cages and longlines were defined according to current speed and depth (Figures A1.2–A1.3) based on data from manufacturers and mariculture practice (Table A1.2 (depth) and A1.3a (current speed).

FIGURE A1.2
Steps to define spatial limits on offshore cages and longlines based on depth and current speed

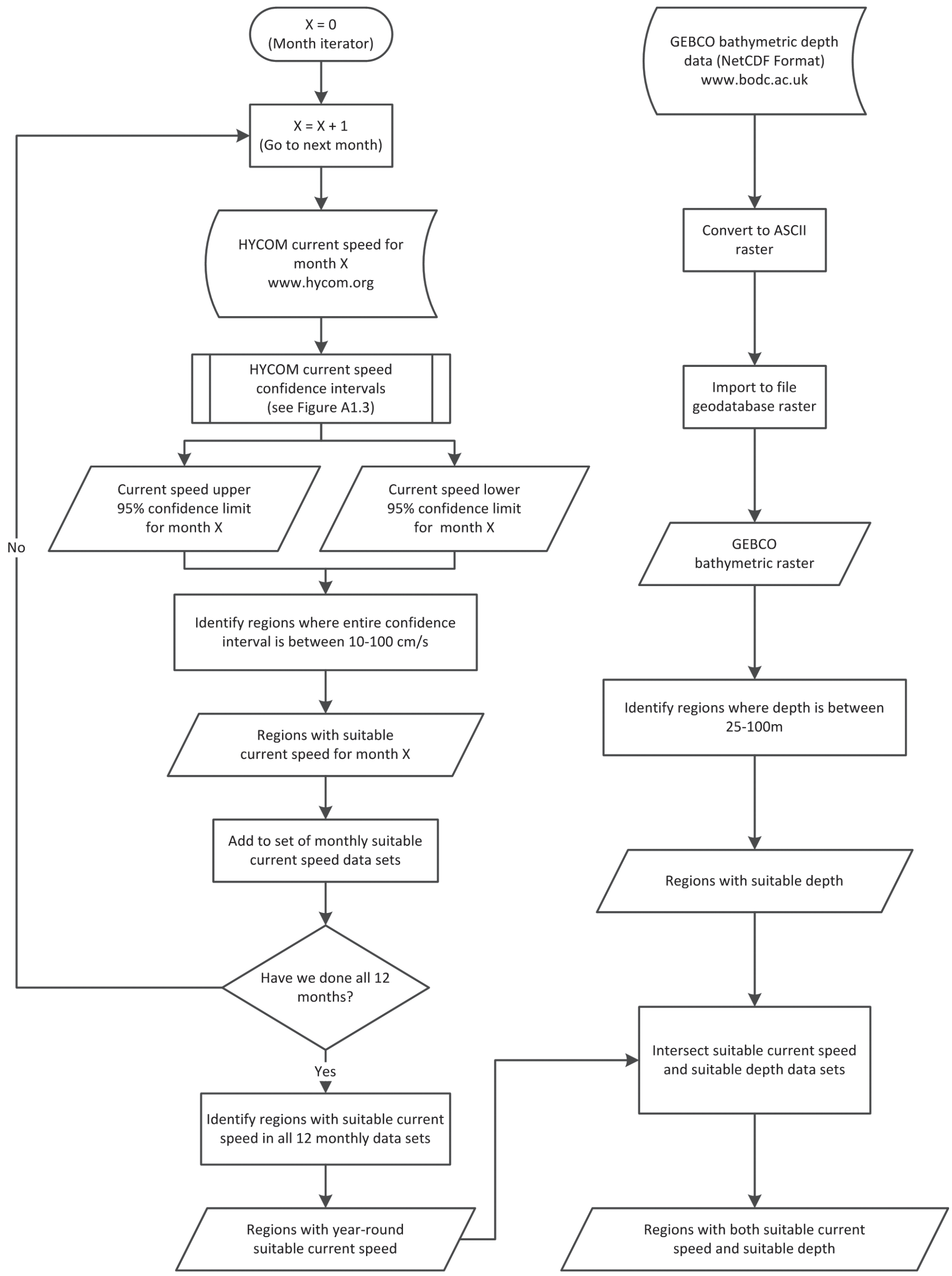
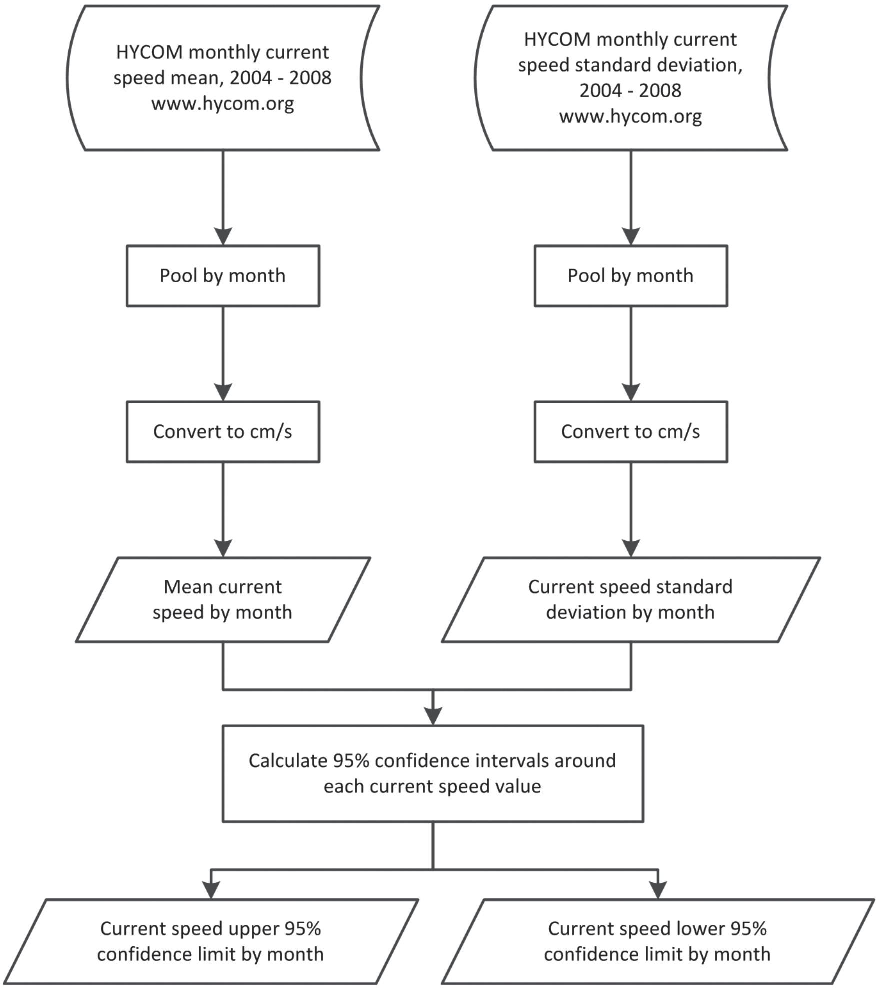


FIGURE A1.3
HYCOM current speed confidence intervals subprocess



Depth: bathymetric data were extracted from the 2008 version of General Bathymetric Chart of the Ocean (GEBCO), which is a raster data set with cell edge lengths of approximately 0.9 km. In all analyses using this bathymetric data, regions with depths in the desired ranges were converted to polygon feature classes for further analysis.

Horizontal cell size: the GEBCO bathymetric data had 43 200 columns covering 360 degrees of longitude (40 075 km equatorial circumference). This equals to 0.92766 km per cell width along the equator. This east-west distance decreases when moving towards the poles. The extreme north and south rows that actually had data were < 1 metre in width.

Vertical cell size: the GEBCO bathymetric data had 21 600 rows covering 180 degrees of latitude (20 004 km from the North Pole to South Pole), equal to 0.92611 km per cell. This north-south distance is constant for all cells.

Current speed: the current speed data (from HYCOM, representing current speed at 30 m depth) included separate monthly data sets over a 5-year period from 2004 to 2008. Therefore, data were pooled by month before calculating the confidence intervals. Note: the original HYCOM current speed units are in metres per second, so these values were converted to centimetres per second for the final threshold analysis. Summarized monthly mean, standard deviation and upper/lower 95 percent confidence limits for current speed were calculated as follows:

Pooled Monthly Mean $\bar{x} = \dfrac{\sum_{i=2004}^{2008} \bar{x}_i N_i}{\sum_{i=2004}^{2008} N_i}$

where:

$\bar{x}_i$ = mean observed value for the month

N_i = number of days in month

i = Each month summed over 5-year period (2004 - 2008).

Pooled Monthly Standard Deviation $\sigma = \sqrt{\dfrac{\sum_{i=2004}^{2008} (N_i - 1)s^2}{\sum_{i=2004}^{2008} (N_i - 1)}}$

where:

s_i = standard deviation for the month

N_i = number of days in month

i = Each month summed over 5-year period (2004 - 2008).

95% Confidence Limits $= \bar{x} \pm t_{(0.975,N-1)} \dfrac{s}{\sqrt{N}}$

where:

$\bar{x}$ = pooled mean current speed for this month, combined over 5-year period

$t_{(0.975,N-1)}$ = critical value from t distribution at $N - 1$ degrees of freedom

N = Number of days in pooled mean, combined over 5-year period

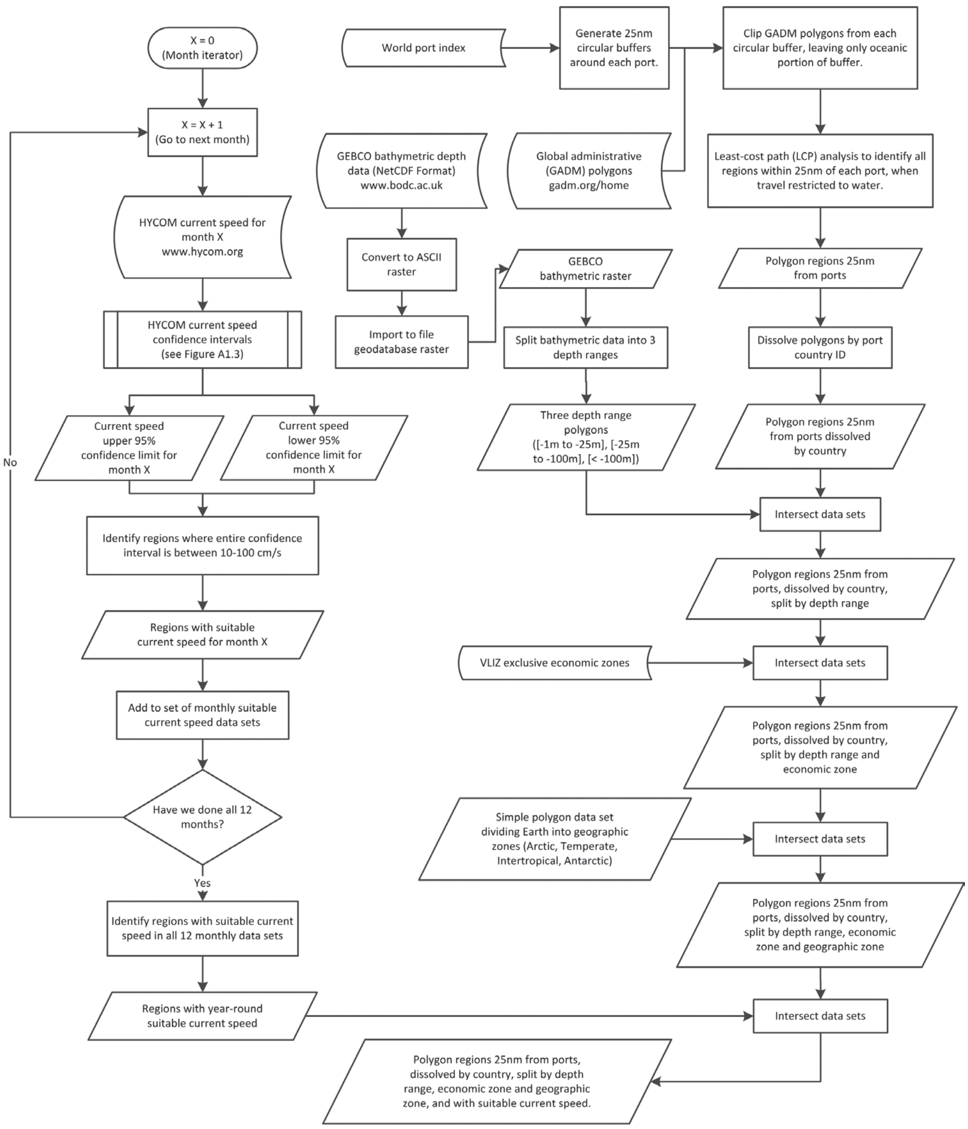
Horizontal cell size: HYCOM current speed data had 4 500 columns covering 360 degrees longitude (40 075 km equatorial circumference). This equals 8.90556 km per cell width along the equator. This east-west distance decreases when moving towards the poles. The extreme north and south rows that actually had data were < 2 km in width.

Vertical cell size: HYCOM current speed had 2 100 rows covering approximately 168 degrees latitude (~18,665 km from North Pole to –78°), equal to 8.88810 km per cell. This north-south distance is constant for all cells.

Distance from a port and reliable access to offshore spatially define the cost-effective area for offshore mariculture development

Cost-effective areas around ports: several steps were conducted to identify regions that were within 25 nm (46.3 km) of a port, intersected with depth range, current speed and VLIZ exclusive economic zone (Figure A1.4).

FIGURE A1.4
Steps to define cost-effective areas around ports



- Beginning with the 2009 World Port Index, 25 nm (46.3 km) buffer circles were first created around each port location using a custom VBA function. This function creates circles with 180 vertices distributed every 2° around the circle. Each vertex is created a specified distance and bearing from the port, and the new vertex locations are calculated accurately over the curved surface of the planet spheroid using spherical trigonometric functions so that the circles are undistorted by any projection issues.
- This study was only interested in the marine portion of the port buffers, so all land portions were clipped off based on Global Administrative Areas (GADM) polygons.
- This study was only interested in the portion of the port buffers that were within 25 nm travel distance from the ports, so the port buffers were further clipped to this region using a custom VBA function to create a cost-distance raster over each GADM-clipped port buffer polygon. This function calculates the cumulative distance from the port location, where travel is restricted to only the water. Note: this function is reasonably accurate but not perfect. Because of how cost-

distance functions work with raster surfaces, the final data set correctly identifies all locations within approximately 23.5 nm (43.5 km) of the port. It correctly identifies approximately half the locations between 23.5 and 25 nm of the port, and it incorrectly identifies approximately half the locations between 25 and 25.5 nm of the port. Therefore, there is some uncertainty about the area between 23.5 and 25.5 nm of the port. This problem is inherent in raster-based cost-distance algorithms and is unavoidable.

- The port buffer feature class was then intersected with GEBCO-derived Depth Range polygons (–1 m to –25 m), (–25 m to –100 m), (< –100 m).
- Finally, the port buffer feature class was intersected with VLIZ exclusive economic zone polygons.
- This final feature class reflects only maritime areas within 25 nm travel distance of ports, combined by country, and split by depth range and EEZ.

Eventually, the final feature class was intersected with areas favourable for the grow-out of the three species and integrated multitrophic aquaculture (IMTA).

Offshore mariculture potential of three representative species and IMTA of two of them spatially defined by environments favourable for grow-out

Chlorophyll-*a*, sea surface temperature and current speed: the raw data for chlorophyll-*a* (CHL2), sea surface temperature (SST) and current speed (CS) included mean values, number of observations and standard deviations per cell in raster format. Using a confidence level of $\alpha = 0.05$, these original rasters were used to generate 95 percent confidence intervals around the mean values. A location would be considered to fall within a threshold if the full confidence interval around the observed value at that location was completely within the upper and lower threshold values. For example, the temperature threshold for cobia was 22–32 °C. A location would only be considered to fall within this temperature range if both the lower confidence limit at that location was ≥ 22° and the upper confidence limit was ≤ 32°. Steps for identifying suitable regions for cobia, Atlantic salmon, blue mussel and IMTA are illustrated in Figures A1.5–A1.10.

FIGURE A1.5
Steps to define regions favorable for cobia grow-out

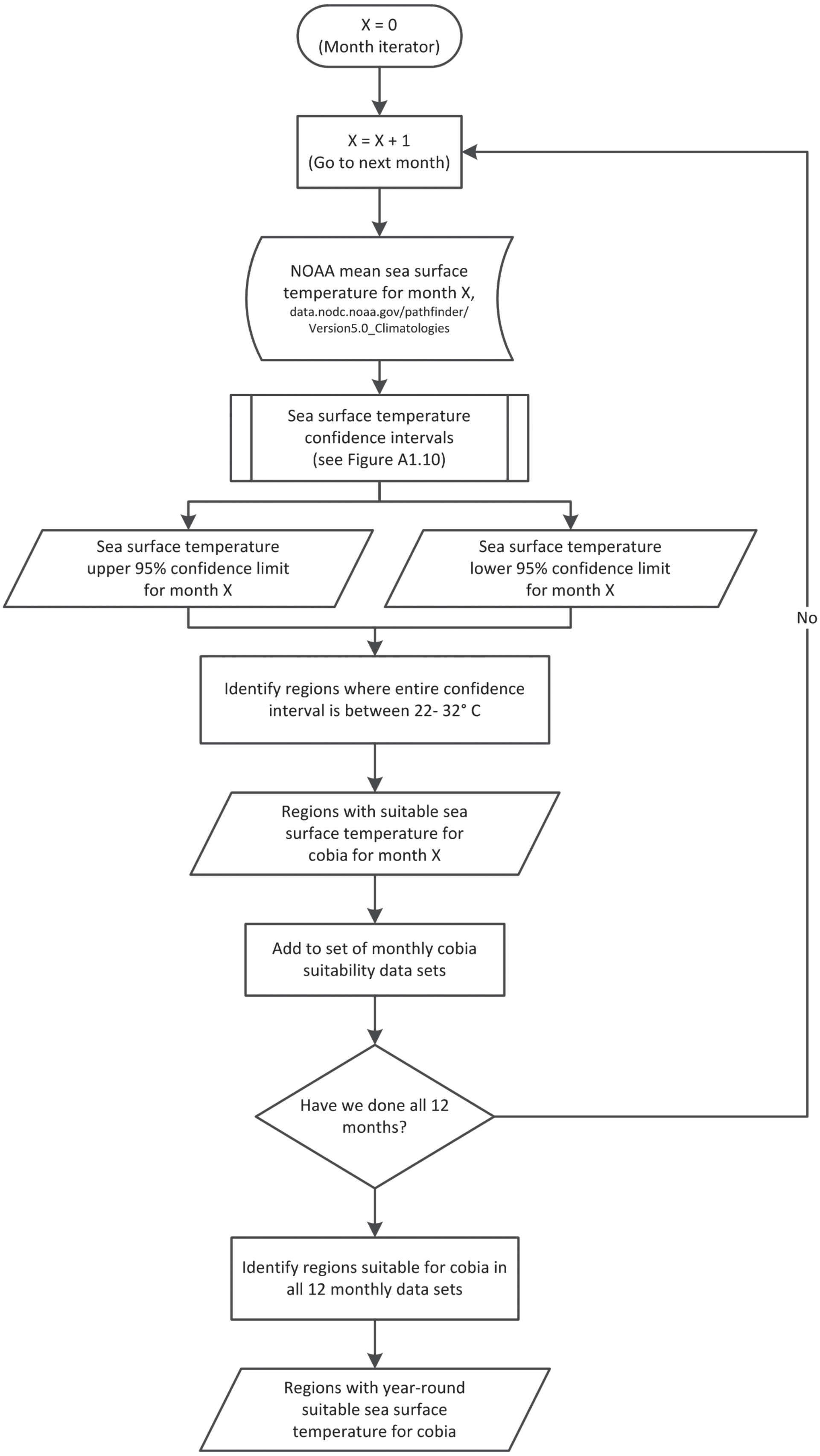


FIGURE A1.6
Steps to define regions favorable for grow-out of Atlantic salmon

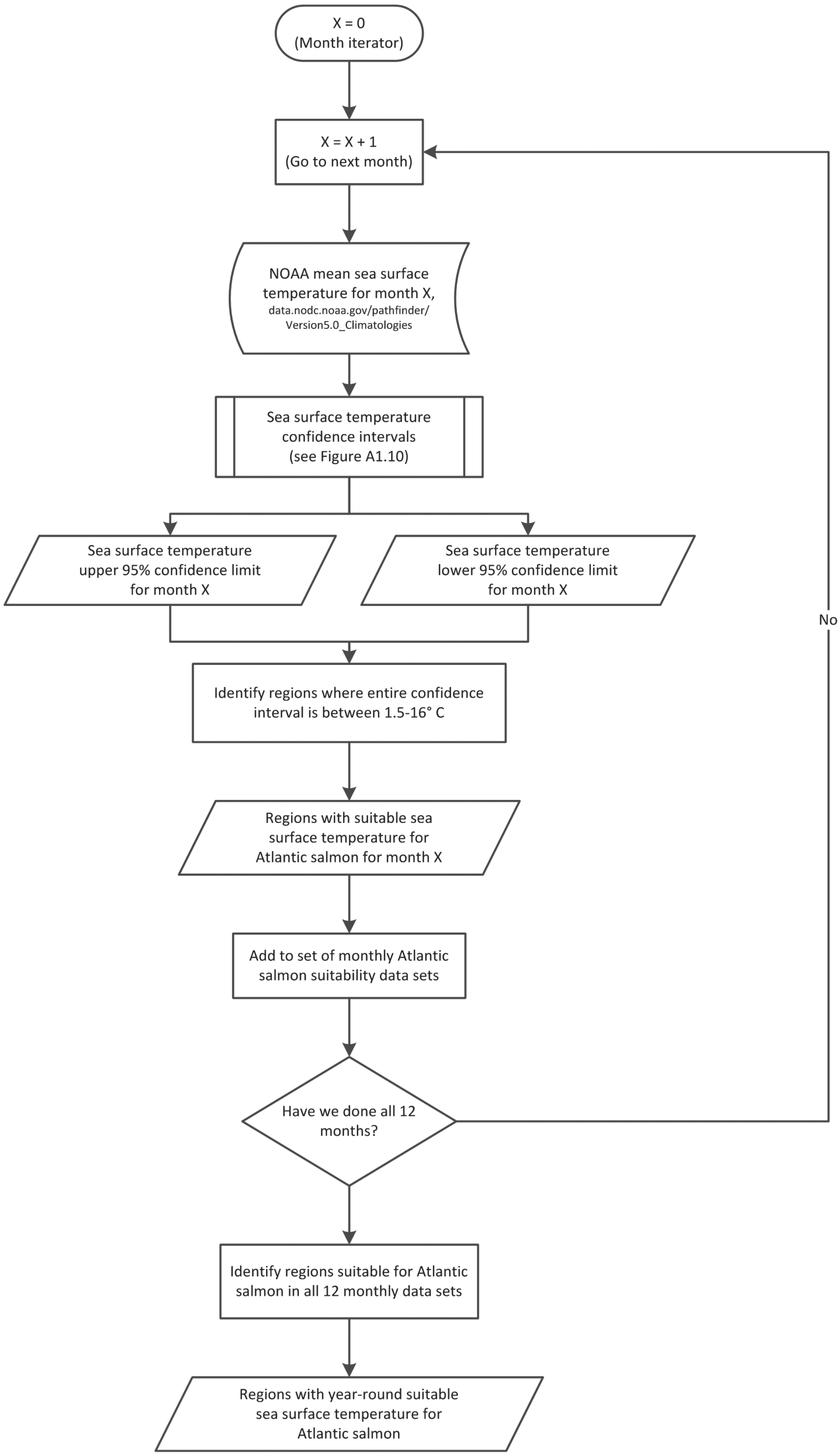


FIGURE A1.7
Steps to define regions favorable for grow-out of blue mussel

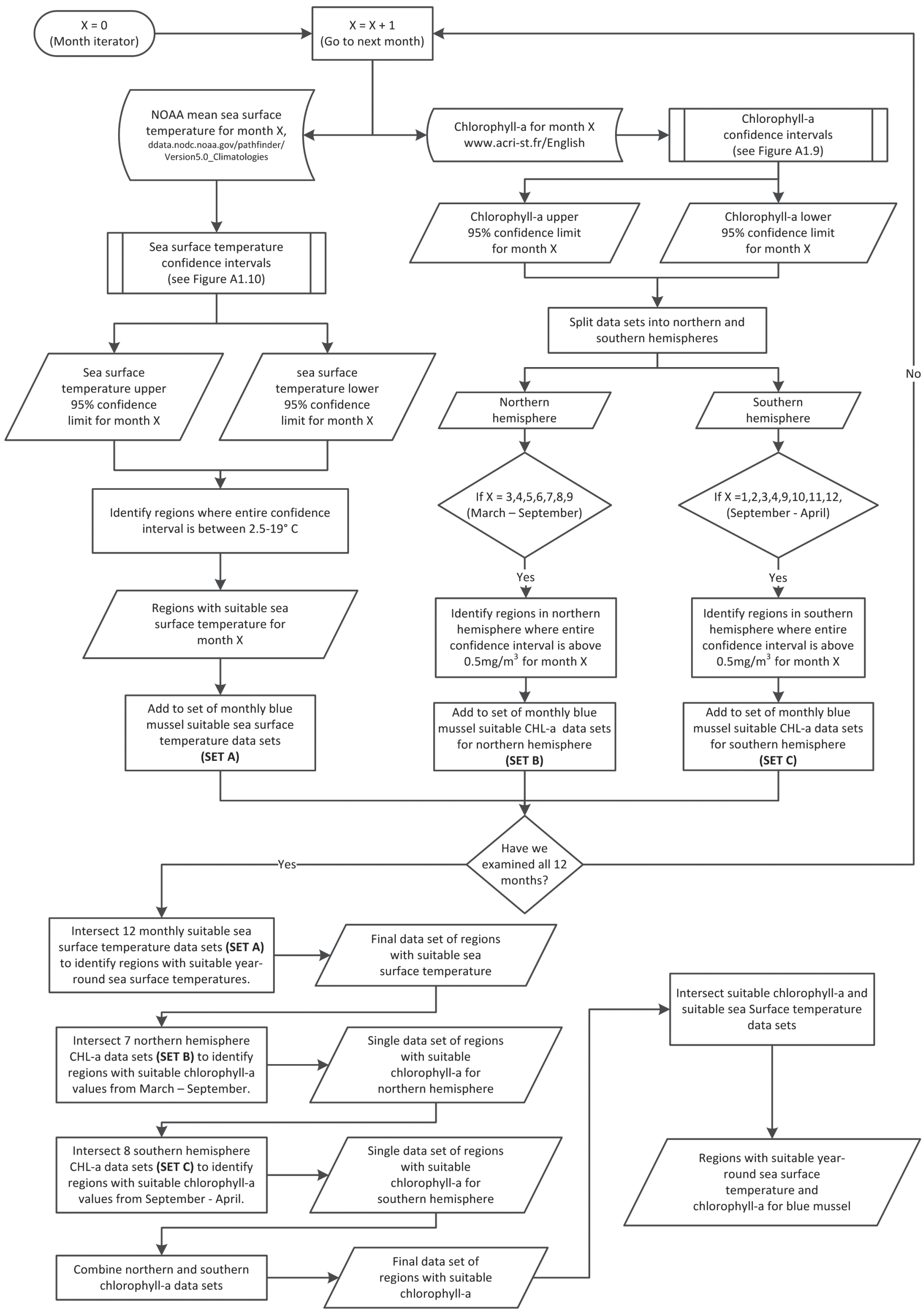


FIGURE A1.8
Steps to define regions favorable for grow-out of Integrated Multi-Trophic Aquaculture (IMTA)

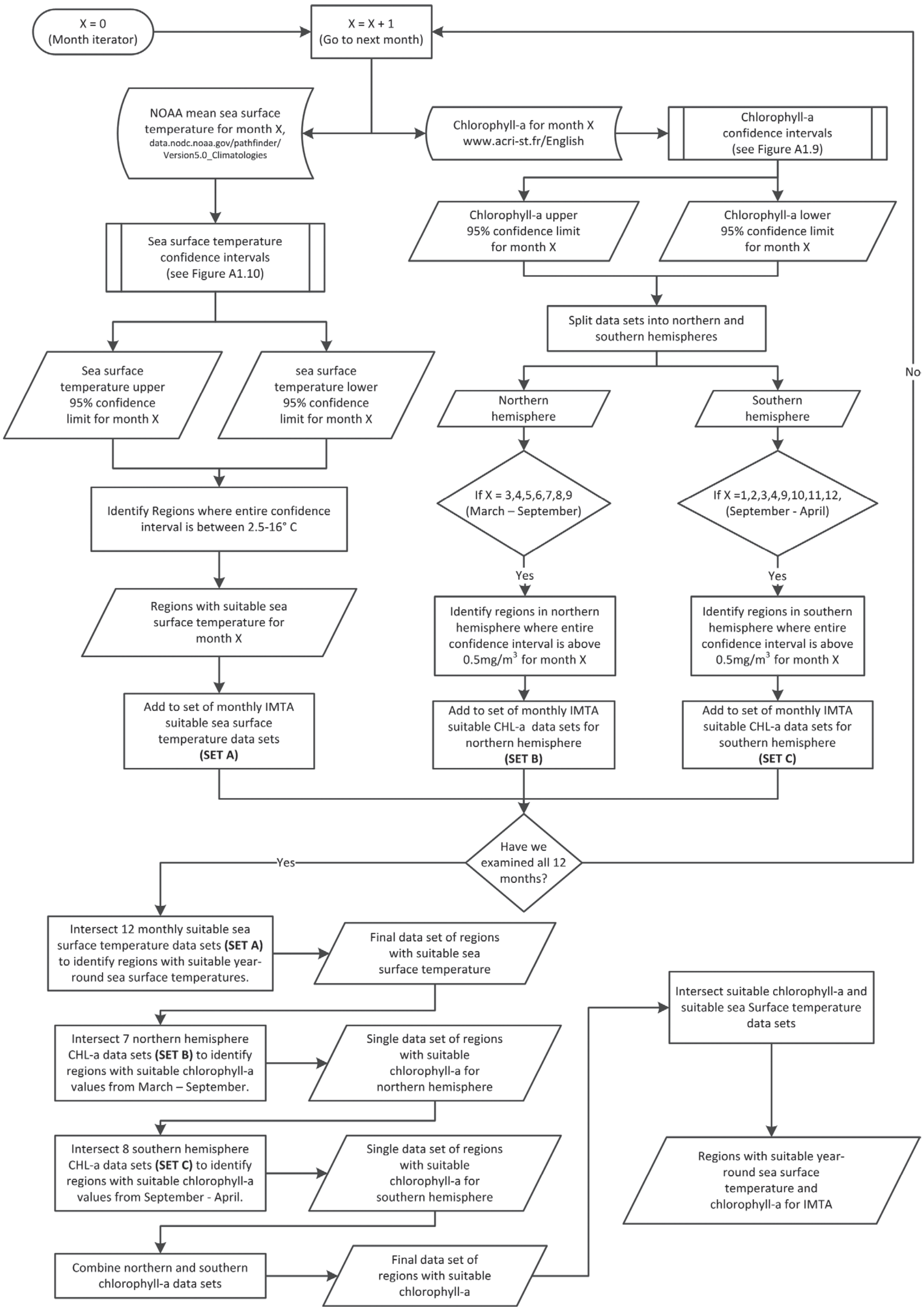


FIGURE A1.9
Chlorophyll-*a* confidence intervals subprocess

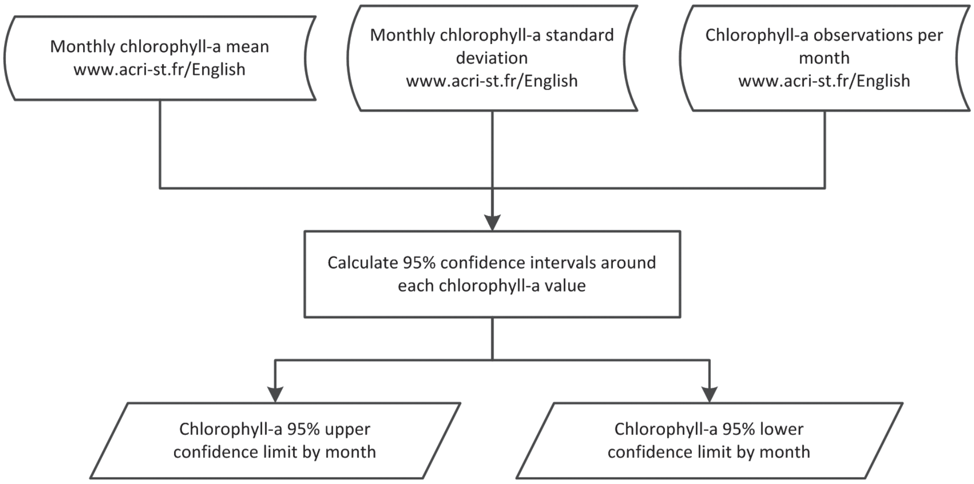
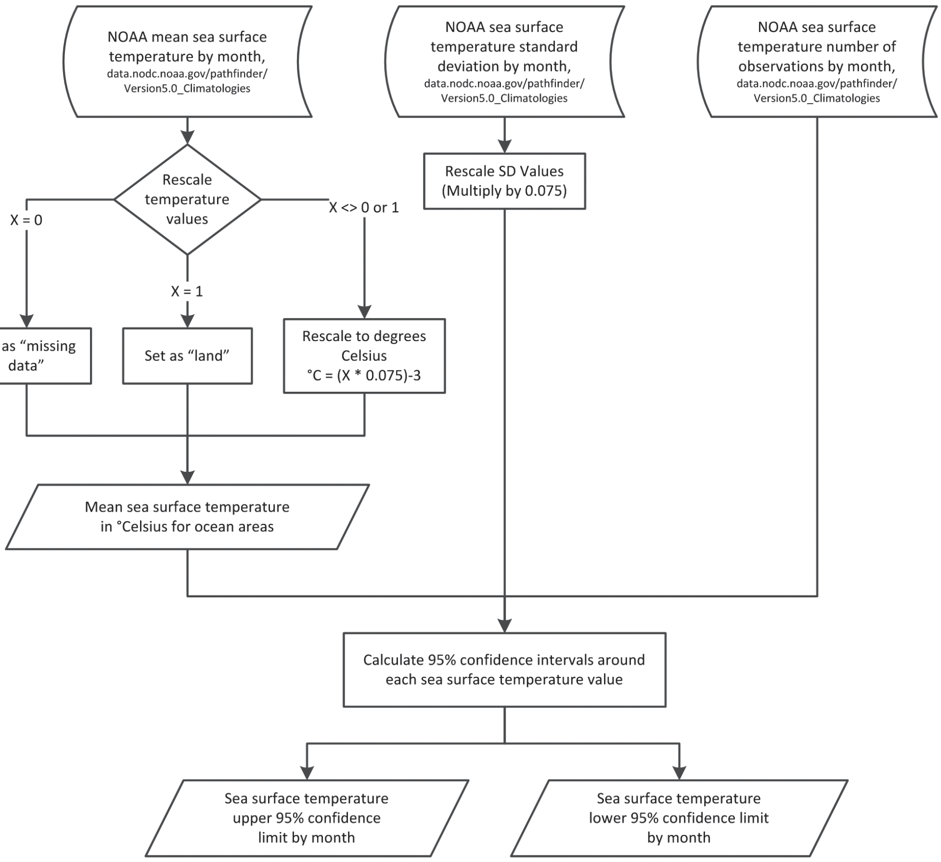


FIGURE A1.10
Sea surface temperature confidence intervals subprocess



CHL2 data was often unavailable at extreme latitudes in the colder months of the year, which complicated the task of identifying areas that met CHL2 thresholds. Therefore, analyses of CHL2 were done both seasonally and by the full year. In the Northern Hemisphere, seasonal data sets were calculated that met threshold requirements for the combined months of March, April, May, June, July, August and September. In the Southern Hemisphere, data sets were calculated that met threshold requirements for the combined months of September, October, November, December, January, February, March and April. These monthly data sets are the monthly averages for the years 2003–2009 (i.e. the "March" data represents the average CHL2 of all the months of March from 2003 through 2009). The final analysis only used the seasonal CHL2 data sets.

The CHL2, CS, SST and bathymetry data were in raster format at different resolutions. The CS had cell edge lengths of approximately 8.9 km, SST cell sizes were ~4.9 km, and CHL2 cell sizes were ~4.6 km. When identifying regions that met various combinations of CHL2, CS and SST thresholds, the finest resolution data set was used to define the resolution of the final raster. For example, an analysis that incorporated both CS and SST rasters would produce a raster with a cell size equal to the SST data because SST had the finest resolution. Bathymetry was at the highest resolution (~0.9 km) and was always converted to a vector polygon feature class of polygons meeting various depth thresholds before additional analysis.

After deriving a final raster delineating all areas that met some combination of thresholds, this final raster was then converted to a polygon feature class for further analysis.

Sea surface temperature: the sea surface temperature data were available as monthly values and, therefore, did not require pooling any data across years. However, to convert them to degrees Celsius, they needed to be rescaled according to the following formula:

True Sea Surface (SST) = [Original SST from HDF files) * 0.075] - 3

Furthermore, original SST values of 1 indicated that they were on land, and values of 0 indicated missing data, so these regions were excluded from the analysis.

95 percent confidence intervals around the mean SST value were calculated according to the following definition:

$$\text{95\% Confidence Limits} = \bar{x} \pm t_{(0.975,N-1)} \frac{s}{\sqrt{N}}$$

where:

$\bar{x}$ = mean SST value for this month

$t_{(0.975,N-1)}$ = critical value from t distribution at N - 1 degrees of freedom

N = Number of SST observations in month (typically between 1 and 34)

Horizontal cell size: sea surface temperature data had 8 192 columns covering 360 degrees longitude (40 075 km equatorial circumference). This equals to 4.89197 km per cell width along the equator. This east-west distance decreases when moving towards the poles. The extreme north and south rows that actually had data were < 1 km in width.

Vertical cell size: sea surface temperature had 4 096 rows covering 180 degrees latitude (20 004 km from the North Pole to South Pole), equal to 4.88379 km per cell. This north-south distance is constant for all cells.

Chlorophyll-*a*: the Chlorophyll-*a* data were available as monthly values and, therefore, did not require pooling of any data. The 95 percent confidence intervals were calculated according to the following definition:

$$\text{95\% Confidence Limits } = \bar{x} \pm t_{(0.975,N-1)} \frac{s}{\sqrt{N}}$$

where:

$\bar{x}$ = pooled mean for this month

$t_{(0.975,N-1)}$ = critical value from t distribution at $N-1$ degrees of freedom

N = Number of CHL2 observations in month

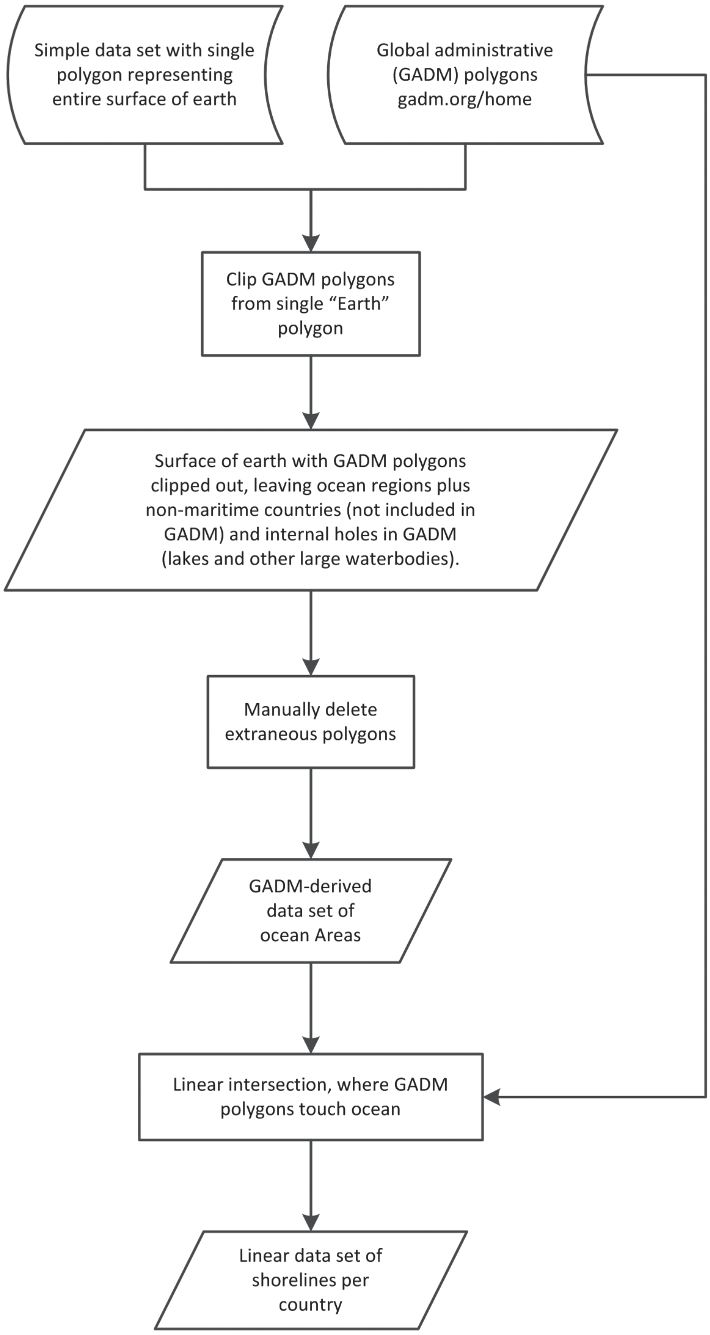
Horizontal cell size: chlorophyll-*a* data had 8 640 columns covering 360 degrees longitude (40 075 km equatorial circumference). This equals to 4.63831 km per cell width along the equator. This east-west distance decreases when moving towards the poles. The extreme north and south rows that actually had data were < 3 km in width.

Vertical cell size: chlorophyll-*a* had 4 320 rows covering 180 degrees latitude (20 004 km from the North Pole to the South Pole), equal to 4.63056 km per cell. This north-south distance is constant for all cells.

Marine protected areas: a data set of marine protected areas was derived from the World Dataset of Protected Areas. This data set was clipped so that it only represents marine areas, and was intersected with geographic zones.

Shorelines: the coastline length data were obtained from the Global Administrative Areas database of administrative boundaries (GADM, Version 1.0), available at www.gadm.org. The polyline data set of marine shorelines was derived by: (i) creating an "ocean" polygon data set by clipping out the GADM polygons from a general background polygon covering the entire earth; (ii) deleting all small polygons from the "ocean" data set that represented lakes or internal holes in the GADM data set; and then (iii) creating a coastline polyline data set by intersecting the GADM polygons with the ocean polygons. This last polyline data set is the linear intersection of all coastal countries with the oceans and, therefore, represents the coastline of all countries that face the ocean. This shorelines layer was essential to determine exactly how much shoreline each country has, and was intersected with other layers (such as the geographic zones data set) to determine how much shoreline lies within specific regions. The steps to generate shorelines are illustrated in Figure A1.11.

FIGURE A1.11
Steps to define coastlines



3.2 Integration of data sets

The compiled spatial data were used in two ways: (i) to identify all of the areas meeting the thresholds associated with each criterion; and (ii) to estimate temperatures and chlorophyll-*a* concentrations at specific mariculture locations. This approach also allowed these suitability thresholds to be compared with temperatures and chlorophyll-*a* concentrations actually experienced in inshore mariculture practice and to measure temperature and chlorophyll-*a* offshore of inshore mariculture locations.

Raster data sets were manipulated in ArcGIS 9.3 as described above, vectorized and imported to Manifold as shapefiles. In Manifold, the shapefiles became drawing (map) components in map projects. Each map project represented a separate analytical step (e.g. identifying the areas with depths suitable for cages and longlines). The output from each project consisted of a drawing and an associated table. Component outputs from individual projects were then sequentially integrated in subsequent projects (e.g. spatial integration of depths and current speeds) to obtain the results set out in Chapter 4. Topology overlay was the basic GIS tool used to spatially integrate the spatial data sets. Selection by query using spatial Structured Query Language was employed to organize the results into meaningful classes. Tables were exported to Microsoft Excel 2010, where the data were manipulated in pivot tables to provide the estimates of potential by EEZ and nation as surface area, which were then reported as tables and charts. Manifold also was used to arrange individual drawings into layers in maps and to add legends and labels to them, which were then exported as images that, in turn, became the map figures in this document.

The analysis conducted for this technical paper was primarily interested in cumulative areas that met various criteria (in which case slivers contributed very little to the cumulative total) and, therefore, the results were not significantly influenced by the potential effects of sliver[8] polygons. The data were also not the types that typically cause large numbers of slivers.

3.3 Comparisons of offshore potential with inshore mariculture locations and verification

Comparisons of predicted offshore potential with inshore mariculture practice at national and subnational levels and verifications at offshore mariculture sites

Three kinds of comparisons were made: (i) national-level comparisons of mariculture production based on FAO statistics (FAO Statistics and Information Branch of the Fisheries and Aquaculture Department, 2012) of the three species with national-level offshore mariculture potential of the species; (ii) known inshore mariculture locations of cobia, Atlantic salmon and blue mussel, obtained through a literature review, contacts with government entities in British Columbia, Canada, Ireland, the Kingdom of Norway and the People's Democratic Republic of China, and with commercial farmers in eastern Canada and several other countries, were compared with areas identified by the analyses as possessing offshore mariculture potential; and (iii) offshore mariculture potential was examined at several offshore cobia farm locations using locational information communicated by commercial farmers. For the first two kinds of comparisons, good correspondence between established inshore mariculture practice and offshore potential indicates that offshore mariculture could be more easily developed using the existing inshore experience, goods and services, and access to markets. Good correspondence also suggests that favourable conditions for grow-out (water temperature and also food availability for the blue mussel) are likely to be found offshore from existing inshore mariculture installations. The third kind of comparison actually tests predicted potential against the locations of functioning offshore farms. Results from this analysis are described in detail in Chapter 5 of the technical paper.

[8] A sliver polygon is a small remnant polygon resulting from an intersection operation between two or more polygons.

TABLE A1.1

Characteristics and sources of spatial and attribute data used in GIS analyses

Statistics	Resolution	Year	Description	Source
Mean mariculture production (tonnes)	N.A.	2004-2008	Data by country and territory averaged over the period indicated. Hong Kong Special Administrative Region included with China; Channel Islands separated into Guernsey and Jersey.	FAO FishStat Plus; www.fao.org/fishery/statistics/software/fishstat/en
Mariculture intensity (tonnes/km)	N.A.		Mean mariculture production 2004–2008 as a function of coastline length (km).	Derived

Spatial data	Resolution/ scale	Year	Description	Source
VLIZ Maritime Boundaries Geodatabase, Version 5 of 10 October 2009	N.A.	2009	Freely downloadable exclusive economic zones in shapefile format. The database includes two global GIS-layers: one contains polylines that represent the maritime boundaries of the world countries, the other one a polygon layer representing the exclusive economic zone of countries. The database also contains digital information about treaties.	Flanders Marine Institute, Belgium; www.vliz.be/vmdcdata/marbound/index.php
General bathymetric chart of the oceans (GEBCO), GEBCO_08 Grid, 2009	0.9 km		A global 30 arc-second (nominally 0.9 km resolution) grid that is freely downloadable after registration. Software is available to download for viewing and accessing data from the global grid files in ASCII as well as in netCDF format.	British Oceanographic Data Centre; www.bodc.ac.uk/data/online_delivery/gebco/

Spatial data	Resolution/ scale	Year	Description	Source
Current speed (cm/s) Global HYbrid Coordinate Ocean Model (HYCOM) and Navy Coupled Ocean Data Assimilation (NCODA)	8.9 km	2004-2008	The HYCOM/NCODA model-data link was used to make a monthly hindcast of mean monthly current speed and standard deviation from January 2004 to August 2008 at a depth of 30 m and at a resolution of 1/12 degree (nominally about 8.9 km resolution).	The current speed data were processed by HYCOM staff and delivered via the Internet. An overview of the HYCOM evolution and process is provided by Chassignet *et al.* (2009) and also at www.hycom.org
World Port Index	N.A.	2009	The freely downloadable World Port Index contains the location and physical characteristics of and the facilities and services offered by major ports and terminals worldwide (approximately 3 700 entries), in shapefile format.	National Geospatial Intelligence Agency, United States of America; http://msi.nga.mil/NGAPortal/MSI.portal;jsessionid=LknZMdkMlgXnfGhvRGDdLTmSvySYnZJLvR9x1WyvqvxybLJVbrqm!251225267!NONE?_nfpb=true&_pageLabel=msi_portal_page_62&pubCode=00
Sea surface temperature	4.9 km	1985–2001	Monthly climatology of SST from the National Oceanic and Atmospheric Organization (NOAA), United States of America, from 1985 to 2001 at a nominal 4.9 km resolution.	http://data.nodc.noaa.gov/pathfinder/Version5.0_Climatologies
Coastal chlorophyll-*a* (CHL2, or Case II)	4.6 km	2003–2009	Monthly mean CHL2 concentration from 2003 to 2009 using a MERIS algorithm at 4.6 km nominal resolution.	Phillipe Garnesson, ACRI-ST, Sophia-Antipolis, France; www.acri-st.fr/English/

Spatial data	Resolution/ scale	Year	Description	Source
2010 World Database on Protected Areas. Annual release – data set number 2C Global data set of marine protected areas	N.A.	2010	All national and international marine protected areas, including national sites not formally declared by government (e.g. proposed). Includes MPA Global 2008 and any other sites that have been identified as having a "marine" component. Data are provided in shapefile format, and GIS capable software is required to view it. Data are freely downloadable after registration.	www.wdpa.org/
Geographic zones	N.A.	2010	Arctic, Northern Temperate, Intertropical, Southern Temperate and Antarctic Zones.	These polygons were generated within this study based on the Tropics of Cancer and Capricorn, and on the Arctic and Antarctic Circles
GADM database of Global Administrative Areas, Version 1	N.A.	2010	GADM is a freely downloadable spatial database of the location of the world's administrative boundaries. The data are available in shapefile, ESRI geodatabase, RData and Google Earth kmz format .	http://gadm.org/home
Coastline length (km)	N.A.	2010	Data by country and territory, derived from GADM (Global Administrative Areas) v. 1.	Calculations made within this study. See Figure A1.11 above that describes the approach in detail

Terminology: N.A. = Not applicable as they are in vector format.

TABLE A1.2
Depth characteristics of experimental and commercial sea cage and longline installations and specifications from manufacturers

Entity	Location	System type	Depth at site (m), or manufacturer's specification	Sources
Sea cages for fish				
Snapperfarm, Inc.	Puerto Rico, United States of America	SeaStation™ offshore submersible	30	O'Hanlon *et al.* (2001)
Cates International	Hawaii, United States of America	SeaStation™ offshore submersible 3000	31	Bybee and Bailey-Brock, (2003), p. 121
Kona Blue Water Farms	Hawaii, United States of America	SeaStation™ offshore submersible 3000	61–67	Kona Blue Water Farms (2003)
University of New Hampshire	New Hampshire, United States of America	SeaStation™ fish cage (SS600)	52	Langan and Horton (2005)
Gulf of Mexico Offshore Aquaculture Constortium	Mississippi, United States of America	SeaStation™ fish cage 600 m3	25	www.masgc.org/oac/Phase%201%20RP1.pdf
Ocean Spar LLC (manufacturer)	Washington, United States of America	SeaStation fully submerged or floating	> 25	www.oceanspar.com/files/OceanSpar_ SeaStation.pdf
Farmocean International (manufacturer)	Sweden	Farmocean 4500	25	www.farmocean.se/General.pdf
SUBflex	Israel	SUBflex single point mooring	40–55 (12 m diameter cage) 0–60 (16 m diameter cage) 50–80 (18 m diameter cage)	SUBflex Open Ocean Net SPM cages; www.subflex.org
Ocean Farm Technologies	Manufacturer's specification	Aquapod A212, A3600, A7000	20–50 - 32–50 - 35–50	Ocean Farm Technologies "Aquapod Site Selection" (www.oceanfarmtech.com) and C. Stock, personal communication (2009)
Workshop on open ocean aquaculture	United States of America	Sea cages with multiple anchors	Comment: Mooring > 100 m a challenge owing to large footprint, capital and maintenance cost of anchoring system	Browdy and Hargreaves (2009)
Asia-Pacific Ocean Research Center, National Sun Yat-sen University	Taiwan Province of China	Gravity cages	30–50 ideal range of water depth for net-cage implementation in the open sea	Huang, C.C., Tang, H.J. and Liu, J.Y. (2008)

TABLE A1.3A
Current speed in mariculture practice for sea cages and longlines

Current speed (cm/s)	Comment	Cage type	Source
60	Not to exceed	General comment to avoid deformation	Beveridge (1996)
103–129	Not to exceed	Farm Ocean 4500	www.farmocean.se/General.pdf
100	90% of cage volume is retained	Ocean Spar SeaStation	Scott and Muir (2006); http://ressources.ciheam.org/om/pdf/b30/00600651.pdf
150–170	"Anti-current" offshore	DFC type	Chen *et al.* (2007) in Cage Aquaculture (Table 4, p. 59); www.fao.org/docrep/010/a1290e/a1290e00.htm
100–120	"Anti-current" semi-open location	PDW type	
50–100	"Anti-current" semi-open location	HDPE type	
150	"Anti-current"	HDPE type submerged	www.alibaba.com/catalog/11644670/Submerged_Style_HDPE_Deep_Water_Sea_Cage.html
72	Maximum for a 144–625 m^3 cage	LMS type	Hunter,Telfer and Ross (2006), Table 3.1 p. 14; www.aqua.stir.ac.uk/public/GISAP/pdfs/SARF003_Full.pdf
82	Maximum for a 700–800 m^3 cage	C-250 type	
93	Maximum for a 3 000–17 000 m^3 type	C-315 type	
10–75	Range given for three cage models	Ocean Farm Technologies Aquapod A212, A3600 and A7000	Ocean Farm Technologies "Aquapod Site Selection" dated 6/5/09 (www.oceanfarmtech.com) and e-mail dated 24 June 2009 from Chris Stock in Outlook Folder Marne GIS
100	Currents that exceed 100 cm/s not generally recommended	Sea cages in general	James and Slaski (2007) (in PNA)

TABLE A1.3B

Current speed in mariculture practice for finfish and mussels

Current speed cm/s	Comment	Species	Source
> 10	To assure sufficient water quality within a cage, currents should remain above 10 cm/s for a major part of the tidal cycle.	Salmon	Tlusty, Pepper and Anderson (2005) citing Puls and Sunderman (1990).
1–9, 1–7, 1–22, 1–10, 1–45 5–10, 2–6	Observations at five inshore sea sites and two lake farming sites taken during two visits, from 5 to 8 hours (five sites) up to three days (two locations) at depths of from 22 to 75 m with recorder 1–2 m from the bottom.	Atlantic salmon	Soto et al. (2003)
3–18 (average)	Twenty salmon farms, Bay of Fundy, Canada, with 24-hour deployments corresponding to two tidal cycles.	Atlantic salmon	Peterson et al. (2001); http://publications.gc.ca/collections/collection_2012/mpo-dfo/Fs97-6-2337-eng.pdf
42 (maximum)	Twenty salmon farms, Bay of Fundy, Canada, with 24-hour deployments corresponding to two tidal cycles.	Atlantic salmon	Peterson et al. (2001); http://publications.gc.ca/collections/collection_2012/mpo-dfo/Fs97-6-2337-eng.pdf
> 100	"Sites where current speeds exceed 100 cm/s for extended periods may not be suitable for growing salmon".	Atlantic salmon	Chang, Page and Hill (2005); www.gnb.ca/0027/Aqu/pdfs/BarryDFO2585.pdf
10–110	"Estimated range of no less than 10 cm/s for several hours and no more than 110 cm/s for more than 24 hours".	Relates to Atlantic salmon and blue mussel among other species considered	Macleod (2007) citing Massachusetts Bay Environmental Forecast System Model, UMass Boston. (M. Jiang, personal communication, 2007); http://envstudies.brown.edu/theses/archive20062007/merriellemacleod_thesis.pdf
10–60	"…sites considered optimal for fish farming in pens have current ranges from 10 to 60 cm/s but varies within this range depending on size and species of fish, stocking density and cage design and configuration".	Relates to "marine or salmonid fish"	Rensell et al. (2007), p. 115; www.fra.affrc.go.jp/bulletin/bull/bull19/13.pdf
< 154	Current speeds are to 3 knots (i.e. 154 cm/s) (offshore site).	Cobia	Aqualider: www.aqualider.com.br (out of business late 2010)
13–77 (range)		Cobia	Snapperfarm, Inc., Puerto Rico, United States of America; Benetti et al. (2010)
< 26	Current is variable but mainly north to south with peaks of 26 cm/s and days of slack current.	Cobia; Double ring olarcirkel, 40, 60 and 100 m circumference	Marine Farms Belize; www.marinefarmsbelize.com
13–129	Current 0.25 knot (13 cm/s) average, max 2.5 knots (129 cm/s).	Cobia; SeaStation 6400, Aquapod 7000 and 100 m Aqualine	Open Blue Sea Farms, Panama; www.openblueseafarms.com
10–50	Siting study for Snapperfarm; mean is 10 and max is 50 observed.	Cobia	Rensell, Kiefer and O'Brien (2006); www.lib.noaa.gov/retiredsites/docaqua/reports_noaaresearch/cobia_aquamodel_final_report.pdf

Current speed cm/s	Comment	Species	Source
< 50	Mainly traditional cobia cages, but some offshore cages at 11 locations.	Cobia	Guangdong and Hainan provinces, China. (C. Zhu, personal communication, 2011)
55	Offshore waters of Penghu Islands, Taiwan Province of China.	Cobia	Miao et al. (2009)
9	Offshore waters of Pingtung County, Taiwan Province of China.		
70–104	Highest speeds encountered as ocean-gyre currents.	*Serioala rivoliana*; Ocean Spar SeaStation cages installed at Keahole Point, Hawaii, (United States of America) 1.6 km offshore	Loverich (2010)
31–103	SeaStation 3000 and 5400, 4.5 km offshore, Jeju province, Republic of Korea.	Parrotfish (*Oplegnathus fasciatus*)	Lim and Lee (no date); www.yslme.org/doc/rmc/Presentation/HanKyu%20lm.pdf
129	Design specification.	Gilthead bream (*Sparus aurata*); SUBflex single-point mooring	12 km offshore in 65 m (R. Tishler, personal communication, 2011).
51–77	Constant speed experienced.	51–77	Constant speed experienced.
103	Maximum experienced.	103	Maximum experienced.
5–50	• "Class I Production up to 20 000 pounds per year (9 072 kg per year). • Minimum depth of 35 feet (10.6 m) for a current velocity of 5 cm/sec (0.1 knots) to a minimum depth of 20 feet (6.1 m) for current velocities of 40 cm/sec (0.8 knots) or greater Class II Production between 20 000 to 100 000 pounds per year (9 072 to 45 360 kg per year). • Minimum depth of 45 feet (13.7 m) for a current velocity of 5 cm/sec (.01 knots) to a minimum depth of 25 feet (7.6 m) for current velocities of 50 cm/sec (1.0 knots) or greater Class III Production over 100 000 pounds per year (45 360 kg per year). • Minimum depth of 60 feet (18.2 m) for a current velocity of 5 cm/sec (0.1 knots) to a minimum depth of 40 feet (12.1) for current velocities of 50 cm/sec (1.0 knots) or greater.	Finfish	Langenburg and Sturges (1999), Table 2. There is an appendix with a chart relating current speed, production and depth from which the data on the left have been derived. These estimates are from the point of view of environmental protection rather than from maximizing production, it seems.
> 50	SeaStation SS600 and SS3000 cages 10 km offshore of New Hampshire, United States of America, with current speed "often exceeding 50 cm/s".	Atlantic halibut, Atlantic haddock, Atlantic cod	Fredricksson et al. (2003)
10–50	Optimal with lesser speeds affecting fillet quality and greater speeds resulting in a rapid increase of the feed conversion ratio with cultivation becoming financially unattractive.	Gilthead bream	Ferreira, Saurel and Ferreira (2012)

Current speed cm/s	Comment	Species	Source
N/A	"At a current speed of 15 cm/sec, the water at a site is exchanged about 100 times per day. An exchange rate of 2–3 times is typically needed to keep the levels of nutrients in the water column lower than the critical load."	N/A	Grøttum and Beveridge (2007), citing Olsen, Slagstad and Vadstein (2005) p. 148.
5–20 good; < 1 and > 50 poor		Not named	Halide (2008) Appendix 1 (appears to be modelling for unnamed fish species in tropical waters); http://data.aims.gov.au/cads/CADS_TOOL_Technical_Guide.pdf
< 5	Very weak current, poor mass flux and inconsistent current direction. Depletion likely at the centre of farms. Only suitable for low-density farming or spat holding.	*Perna canaliculus* and *Mytilus galloprovincialis*	Inglis, Hayden and Ross (2000), Box table, p. 21
5–10	Weak current velocities of generally widely varying direction leading to some depletion at centre of farm.	*Perna canaliculus* and *Mytilus galloprovincialis*	Inglis, Hayden and Ross (2000), Box table, p. 21
10–20	Moderate-low depletion that may be more marked at downstream end of farm. Depletion is more likely to be observed in centre of farmed area.	*Perna canaliculus* and *Mytilus galloprovincialis*	Inglis, Hayden and Ross (2000), Box table, p. 21
> 20	Strong current flow. Little depletion but cumulative effect of many ropes longlines in the direction of flow could result in (remainder of text is missing from the original article).	*Perna canaliculus* and *Mytilus galloprovincialis*	Inglis, Hayden and Ross (2000), Box table, p. 21
15–20	Bottom culture (moderate grow-out densities).	*Mytilus edulis*	Newell (2001)
5	Longlines, if given adequate spacing.	*Mytilus edulis*	Newell (2001)
10–15	Rafts in order to prevent depletion.	*Mytilus edulis*	Newell (2001)
10–30	Offshore longline.	*Mytilus edulis*	R. Langan, personal communication, 2009
< 10; infrequently up to 50	Hawke Bay, North Island, New Zealand.	Bivalve shellfish, including greenshell mussels, *Perna canaliculus*	Cheney et al. (2010)
< 15–30	Opotiki, North Island, New Zealand.	Bivalve shellfish, including greenshell mussels, *Perna canaliculus*	Cheney et al. (2010)

TABLE A1.4A

Temperatures for grow-out of cobia

Temperature or range	Comment	Location	Source
< 22 No growth		Viet Nam	Nhu *et al.* (2009)
< 18 Stop eating		Viet Nam	Nhu *et al.* (2009)
15 Mass mortality	Five weeks in 2008.	Viet Nam	Nhu *et al.* (2009)
22–30 Mean monthly range		Viet Nam	Nhu *et al.* (2009)
<16 Severe stress, mortalities		United States of America	M. Osterling, personal communication, 2011
16–32; > 20 preferred	Conditions in the wild.	Not stated	Kaiser and Holt (2005)
> 26 Optimal growth	Culture conditions.	Not stated	Kaiser and Holt (2005)
21–22	Feeding activity reduced.	Taiwan Province of China	Miao *et al.* (2009)
19	Feeding ceases.	Taiwan Province of China	Miao *et al.* (2009)
< 16 and > 36	May result in mass mortality.	Taiwan Province of China	Miao *et al.* (2009)
22–32	Optimal temperature range.	Not specified	Miao *et al.*, 2009, citing Chang et al., 1999
25–27 mean spring to autumn; 21–22 mean winter < 16 low temperature		Penghu Archipelago, Taiwan Province of China	Shih, Chou and Chiau (2009)
27–29 Ambient conditions		Snapperfarm, Isla Culebra, United States of America	Rensel, Kiefer and O'Brien, 2006
< 16 High mortality		Penghu Archipelago, Taiwan Province of China	Liao et al. (2004)
23.5–28 year round		Sea cage areas in southern Taiwan Province of China	Liao et al. (2004)
28–32 Highest growth rates; < 20 growth rates decreased	Fish fed to satiation.	Penghu Archipelago, Province of China	Ueng et al. (2001)
26 and above	On growing.	Not stated	Kaiser and Holt (2007); www.fao.org/fishery/culturedspecies/Rachycentron_canadum/en
27–28 year round	On growing.	Open Blue Sea Farms, Panama	B. O'Hanlon, personal Communication, 2011
25–32	On growing.	Snapperfarm, Inc., Puerto Rico, United States of America	Benetti et al. (2010)

TABLE A1.4B

Temperatures for grow-out of Atlantic salmon

Temperature or range	Comment	Location	Source
6–16	Grow best in sites with these temperature extremes.	Generalized	FAO (2011); www.fao.org/fishery/culturedspecies/Salmo_salar/en
0.6–15.6	Winter and summer temperatures not to be exceeded for any length of time.	Maine, United States of America	University of Maine; www.umaine.edu/mainesci/Archives/MarineSciences/salmon-farming.htm
8–18	Optimal range for culture.	Tasmania, Australia	Anon, (2002); www.pir.sa.gov.au/__data/assets/pdf_file/0010/33895/salmon_fs.pdf
12–16	Best growth.	Tasmania, Australia	Anon, (2002); www.pir.sa.gov.au/__data/assets/pdf_file/0010/33895/salmon_fs.pdf
0–21	Tolerate this range.	Tasmania, Australia	Anon, (2002); www.pir.sa.gov.au/__data/assets/pdf_file/0010/33895/salmon_fs.pdf
6–16	Grow-out range.	N/A	Verspoor et al. (2007)
12–16	Preferred range.	Gippsland, Victoria, Australia	Gippsland Aquaculture Industry Network Inc. (2011); http://growfish.com.au/Grow/Pages/Species/Trout.htm
> 22	Not recommended for farming if exceeded on a regular basis.	Gippsland, Victoria, Australia	Gippsland Aquaculture Industry Network Inc. (2011); http://growfish.com.au/Grow/Pages/Species/Trout.htm
0.7	Lowest temperature for survival.	Bay d'Espoir, Newfoundland, Canada	Anon. (2009); www.dfo-mpo.gc.ca/science/enviro/aquaculture/acrdp-pcrda/fsheet-ftechnique/pdf/02-eng.pdf
0–15	This range, along with strong currents and high tides, provide ideal conditions.	Maine, United States of America	Maine Aquaculture Innovation Center (2011); www.maineaquaculture.org/industry/species.html#salmon
0.5–15.2	Measurements from 20 farms over two years.	Bay of Fundy, Canada	Peterson et al. (2001); http://publications.gc.ca/collections/collection_2012/mpo-dfo/Fs97-6-2337-eng.pdf

TABLE A1.4C

Temperatures for grow-out of blue mussel

Temperature or range °C	Note	Location	Source
-1.08–15.6	Range at two commercial farming sites, with two stations per site.	Notre Dame Bay, St. John's, Newfoundland, Canada	Khan, Parrish and Shahidi (2006)
5.5–16.3	Range at shellfish farm.	West Scotland, United Kingdom	Karayucel and Karayucel (1999)
10–18	Range at commercial and experimental sites with improved growth or condition and where food supplies and/or nutrients were adequate (not limited to blue mussel).	Worldwide review	Saxby (2002)
16–22	Exhibit maximum growth in this range.	South Australia	Anon. (2000); www.pir.sa.gov.au/__data/assets/pdf_file/0005/33899/mussels_fs.pdf
4.4–21.1	Range for culture.	Maine, United States of America	Island Institute (1999). The Maine guide to raft culture
4.4–10	Ideal for culture.	Maine, United States of America	Island Institute (1999). The Maine guide to raft culture
18.3	Begin to lose byssal strength.	Maine, United States of America	Island Institute (1999). The Maine guide to raft culture
21.1	Begin to suffer mortality.		
15.8	Optimal temperature for growth (model result).	Prince Edward Island, Canada	Lauzon-Guay, et al. (2006); www.int-res.com/articles/meps2006/323/m323p171.pdf
< 20	Prevent summer mortality.	Eastern North America	Newell (2001)
5–20	Well acclimated for this range.	Worldwide review	Goulletquer, P. (2009); www.fao.org/fishery/culturedspecies/Mytilus_edulis/en
0.30–15.03	Winter and summer daily means.	Lunenburg, Nova Scotia, Canada	Hatcher, Grant. and Schofield (1997)
-2–25	Often exposed to temperatures in this range.	Atlantic Canada	New Brunswick Professional Shellfish Growers Association (2011); www.acpnb.com/statistics.cfm
> 5	Required for somatic and germinal growth.	Eastern North America	Newell and Moran (1989)
5–16	Range affecting growth along with salinity, food quantity and quality.	10 km offshore near Portsmouth, New Hampshire, United States of America	Langan and Horton (2003)

TABLE A1.4D

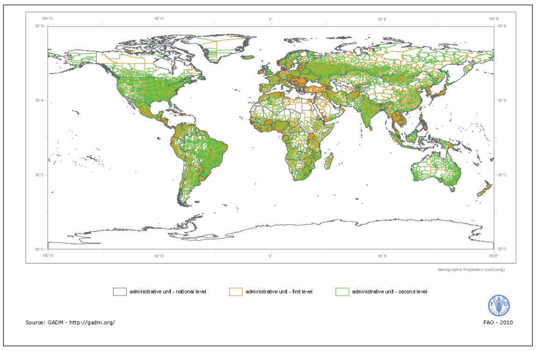
Chlorophyll-concentrations in relation to grow-out of blue mussel

Chlorophyll-*a* concentration mg/m^3	Note	Location	Source
Mean 1–10	Concentrations predominant at sites where bivalves did not appear to be greatly limited by lack of nutrients.	Global review	Saxby (2002)
> 1	Significant growth of Perna canaliculus occurred only when above this concentration.	Marlborough Sounds, New Zealand	Hawkins *et al.* (1999)
< 1 Very poor to poor	Growth of Perna canaliculus in embayments as generic guidelines.	New Zealand	Inglis, Hayden and Ross (2000)
1–2 Moderate	Growth of Perna canaliculus in embayments as generic guidelines.	New Zealand	Inglis, Hayden and Ross (2000)
2–4 Good	Growth of Perna canaliculus in embayments as generic guidelines.	New Zealand	Inglis, Hayden and Ross (2000)
4–8 Ideal	Growth of Perna canaliculus in embayments as generic guidelines.	New Zealand	Inglis, Hayden and Ross (2000)
> 8 Little known	Growth of Perna canaliculus in embayments as generic guidelines.	New Zealand	Inglis, Hayden and Ross (2000)
> 1	Mussel shell growth becomes faster with temperatures 7–8 °C.	Loch Kishorn, Scotland	Karayucel & Karayucel (1999)
< 1– 5	Offshore experimental site with good results for growth and grow-out.	Near Isles of Shoals, New Hampshire, United States of America	Langan and Horton (2005)

4. Global data sets for estimates of offshore mariculture

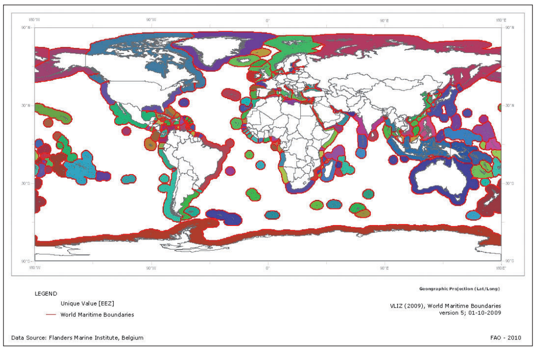
Boundaries of sovereign nations

GADM database of global administrative areas



http://www.gadm.org/

Exclusive economic zones of the world - version 5



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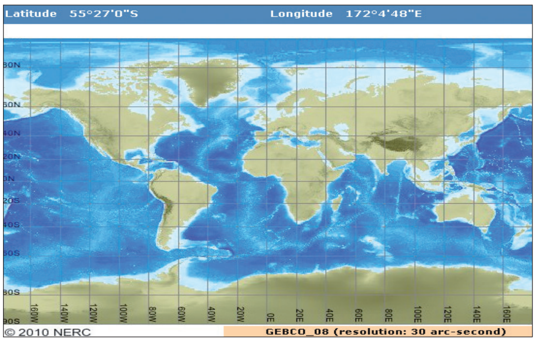
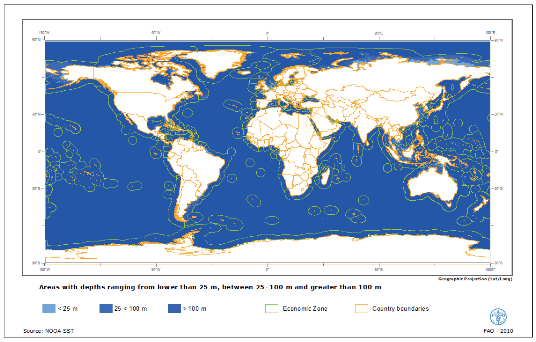
Depth and current speed as the fundamental criteria characterizing the technical limits of present offshore submerged cage and longline culture systems

General bathymetric chart of the Oceans



http://www.gebco.net/

Regions with depths ranging from lower than 25 m, between 25–100 m and greater than 100 m



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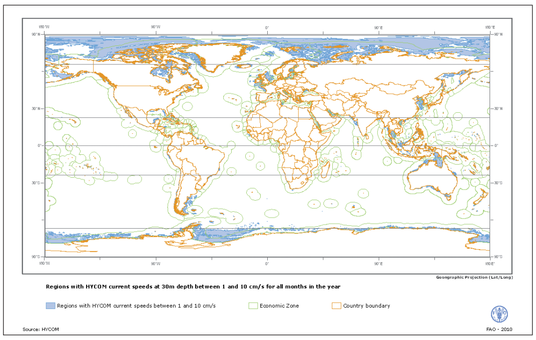
Regions with HYCOM current speeds at 30 m depth between 1 and 10 cm/s for all months in the year



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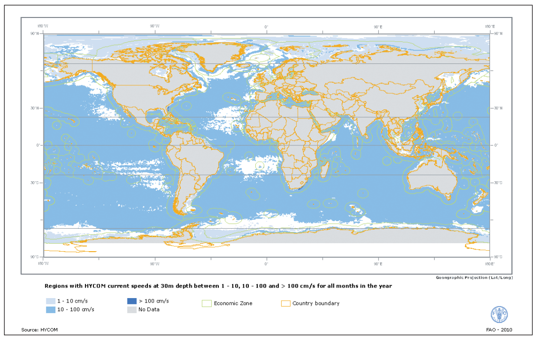
Regions with HYCOM current speeds at 30m depth between 1–10, 10–100 and > 100 cm/s for all months in the year



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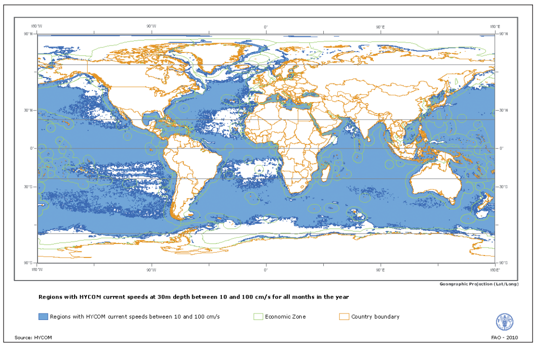
Regions with HYCOM current speeds at 30m depth between 10 and 100 cm/s for all months in the year



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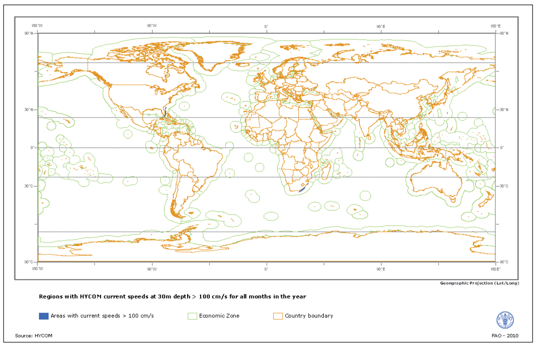
Regions with HYCOM current speeds at 30m depth > 100 cm/s for all months in the year



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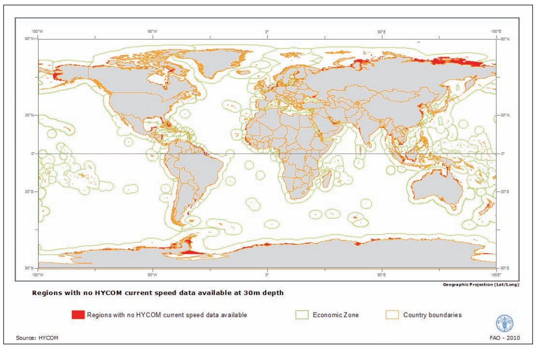
Regions with no HYCOM current speed data available 30m depth



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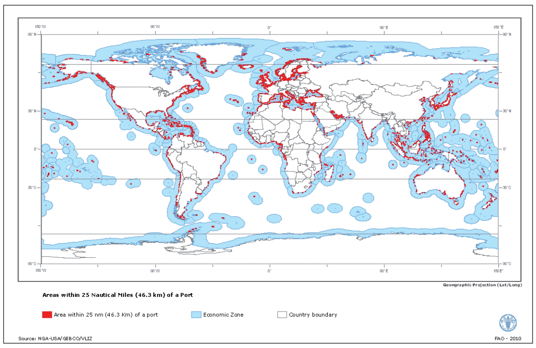
Note: Areas with no current speed data are those with depths less than 30m (i.e. all of the areas close to the shorelines) so they are difficult to see on a world map).

Distance offshore from onshore infrastructure related to economic cost limits on transportation and on reliable access from a port to the sea

Areas within 25 nautical miles (46.3 km) of a port



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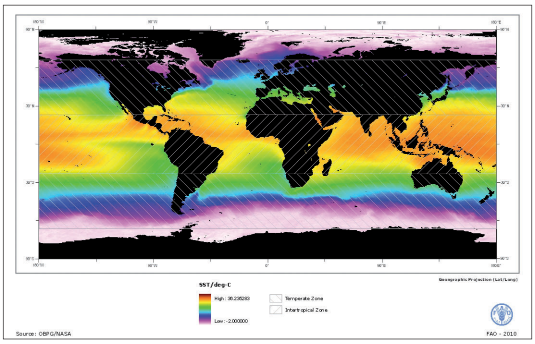
Favourable offshore grow-out environment based on temperature requirements of representative fish and mussels and on food availability measured as chlorophyll concentration for the latter

Aqua MODIS climatology sea surface temperature (Spring 2002–2009)



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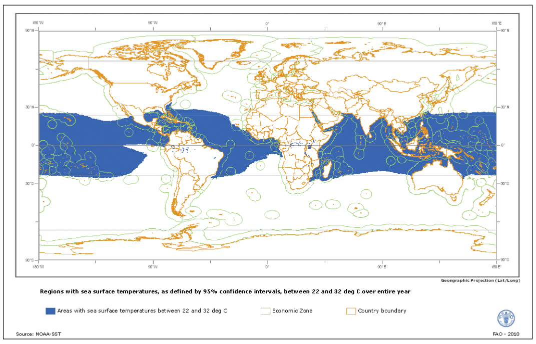
Regions with sea surface temperatures, as defined by 95% confidence intervals, between 22 and 32° C over entire year for Cobia



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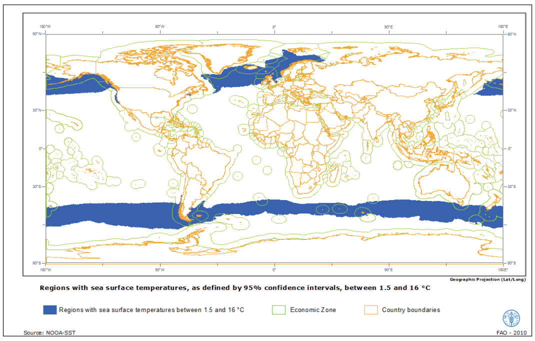
Regions with sea surface temperatures, as defined by 95% confidence intervals, between 1.5 and 16°C over entire year for Atlantic salmon



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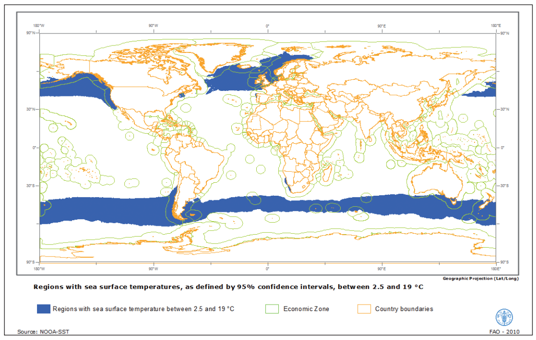
Regions with sea surface temperatures, as defined by 95% confidence intervals, between 2.5 and 19°C over entire year for blue mussel



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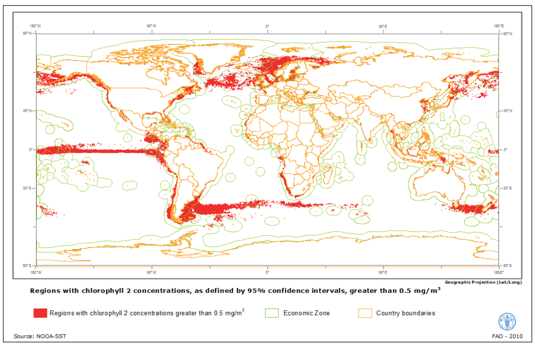
Regions with chlorophyll 2 concentrations, as defined by 95% confidence intervals, greater than 0.5 mg/m3 that were combined for the months available in each hemisphere for the blue mussel



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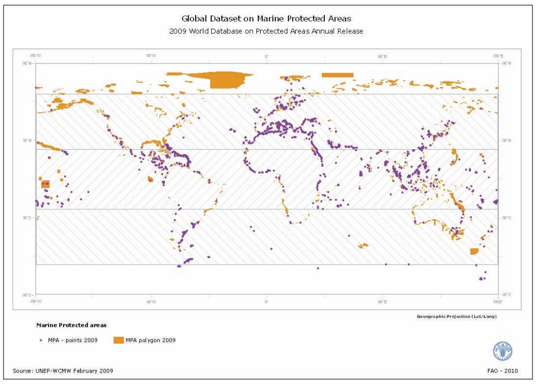
Competing, conflicting and complementary uses of ocean space

2009 World database on protected areas



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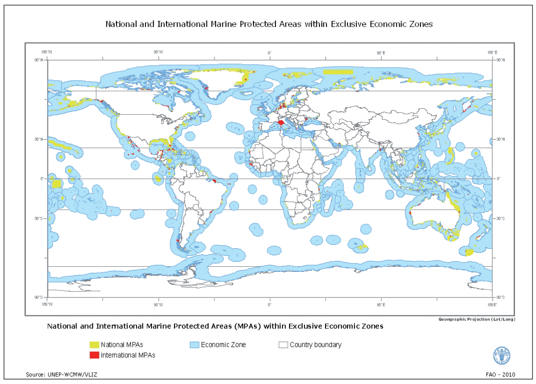
National and international marine protected areas within exclusive economic zones



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Annex 2

Grid-based model: days of grow-out to a harvestable weight for Atlantic salmon among four salmon-producing countries

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Ferreira, J.G. 2013. Grid-based model: days of grow-out to a harvestable weight for Atlantic salmon among four salmon-producing countries. *In* J.M. Kapetsky, J. Aguilar-Manjarrez & J. Jenness. *A global assessment of offshore mariculture potential from a spatial perspective*, pp. 117–121. FAO Fisheries and Aquaculture Technical Paper N. 549. Rome, FAO. 181 pp.

Introduction

The objective of this annex is to illustrate the use of a dynamic grid[9]-based growth model to compare the duration of grow-out of Atlantic salmon at four locations in four of the major salmon-producing countries (Canada, Ireland, Kingdom of Norway and the Republic of Chile). The ultimate aim is to improve estimates of the potential for offshore mariculture by integrating the spatial analytical capabilities of a geographic information system (GIS) with farm-based modelling of variables affecting mariculture sustainability.

The vector[10] approach used in this technical paper (Annex 1) resulted in areas with potential identified by establishing a threshold range of temperatures for favourable grow-out and then locating the areas that have a 95 percent probability of being in that range throughout the year. In this approach, a range of temperatures (thresholds) over large areas were used, and it was assumed that the results would be homogeneous for growth throughout those areas. This is unlikely to be the case. By employing a grid-based approach, there would be much less spatial ambiguity about the conditions in that grid cell's relatively small area, and the actual conditions in that grid cell could be investigated by a simple query. The model could be run in any area of interest within a nation's exclusive economic zone to identify geographically related mariculture development advantages. This is a first step towards that goal specifically aimed at offshore mariculture.

[9] A grid cell (or pixel) is the smallest unit of information in GIS raster data, usually square in shape. In a map or GIS data set, each grid cell represents a portion of the earth, such as a square metre or square mile, and usually has an attribute value associated with it, such as soil type or vegetation class. For the present modelling trial, sea surface temperature (SST) at a nominal 4.5 km2 resolution were used and a time step of one month.

[10] A vector is a representation of the world using points, lines and polygons. Attributes are associated with each vector feature, as opposed to a raster data model, which associates attributes with grid cells.

Methodology

The growth performance of individual salmon was determined by means of a net energy balance model driven by sea surface temperature (SST). The individual growth model developed by Stigebrandt (1999) for growth of Atlantic salmon in Norwegian fjords was used for simulation. This model is based on a conservation of energy equation (Eq. 1, all terms in cal d^{-1}):

(Eq. 1) $$Q_r - (Q_f + Q_N) = Q_s + Q_l + Q_{sda} + Q_g + Q_p$$

Where
Q_r = Energy intake from feeding
Q_f = Energy loss from elimination of faeces
Q_N = Energy loss from nitrogen excretion
Q_s = Energy loss from metabolism
Q_l = Energy loss from locomotion
Q_{sda} = Energy loss from apparent specific dynamic action
Q_g = Energy apportioned to growth
Q_p = Energy loss from reproduction

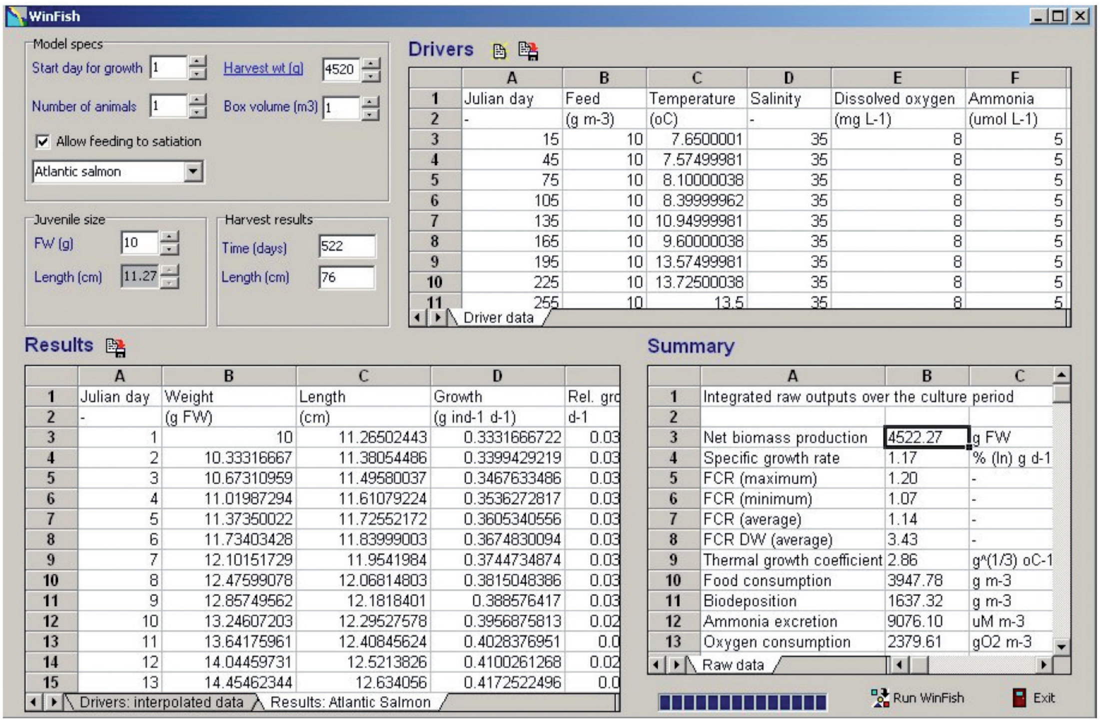
Two of these terms are not explicitly considered. Q_l is considered to be low in inshore culture and is simulated through a small increase in Q_s, and Q_p is inapplicable because animals are harvested prior to reproduction. The change in biomass W with time t is expressed as:

(Eq. 2) $$\frac{dW}{dt} = \frac{Q_g}{C_{fi}}$$

Where
C_{fi} = energy per unit mass of salmon (cal g^{-1})

The model was implemented in C++ and can simulate growth under both food satiation conditions and food limitation, considering multiple fish growing in a control volume. Water temperature and food concentration data are used to force the model.

FIGURE A2.1
Screenshot of the WinFish aquaculture modelling software



The modelling software (WinFish – Figure A2.1) allows either growth for a specific period or up to a user-defined weight to be used as model endpoints. WinFish (Ferreira, Saurel and Ferreira, 2012) is a generic package that currently allows simulation of growth for Atlantic salmon, gilthead bream and tilapia.

Salmon farms from Canada (British Columbia), Ireland, the Kingdom of Norway and the Republic of Chile were selected using expert knowledge, and monthly SST profiles were obtained from an SST climatology (Annex 1, Table A1.1) originally based on satellite remote sensing. These profiles were then used in WinFish, which executes a linear interpolation to provide daily water temperatures as inputs to the individual growth model. A harvest weight endpoint of 4 520 g based on the bioeconomic model developed by Jin (2008) was imposed, one individual was fed to satiation, and the total duration of the growth period required to reach the target weight was determined. The equations in the Stigebrandt model also allow the calculation of relevant environmental data. WinFish provides outputs for these at the management level (bottom line), e.g. total fish biomass, cultivation time, production of ammonia, faeces and oxygen consumption (Figure A2.1 – summary pane). More detailed spreadsheets of daily model outputs are also available (Figure A2.1 – results pane), designed to support scientific interpretation of the results obtained.

Results

Table A2.1 shows the averaged model results at the various locations. Averages are shown because the difference among regions is far greater than differences among farms in the same region (within-region coefficient of variation < 10 percent in all cases).

TABLE A2.1

Management-level synthesis of growth simulations in the four geographic areas

Parameter/region	Ireland	Norway	Chile	Canada
Number of farms	7	6	5	6
Growth period (days)	480	578	431	522
Coefficient of variation across farms (%)	2.77	2.29	7.57	5.05
Biomass (g FW)	4 529	4 535	4 539	4 536
Length (cm)	76	76	76	76
Specific growth rate (% (ln) g d^{-1})	1.28	1.06	1.43	1.17
FCR (maximum)	1.20	1.20	1.20	1.20
FCR (minimum)	1.07	1.07	1.07	1.07
FCR (average)	1.14	1.14	1.14	1.14
FCR DW (average)	3.43	3.42	3.43	3.43
Thermal growth coefficient (g1/3 $°C^{-1}$)	2.84	3.05	2.76	2.88
Food consumption (g m^{-3})	3 944	3 956	3 961	3 953
Biodeposition (g m^{-3})	1 636	1 641	1 643	1 640
Ammonia excretion (uM m^{-3})	9 066	9 084	9 108	9 090
Oxygen consumption (g O2 m^{-3})	2 377	2 382	2 388	2 383

Note: DW = Dry weight; FCR = food conversion ratio; FW = Fresh weight.

Because food limitation and photoperiod are not considered in these results, growth is fundamentally determined by SST and allometry. The fastest mean growth was observed in the Republic of Chile (431 days), and the slowest in the Kingdom of Norway with a mean of 578 days, 34 percent longer. The overall spread was between 395 days (the Republic of Chile) and 591 days (the Kingdom of Norway). The endpoint for biomass corresponds to the simulated weight at the first time step beyond the target weight, and has a maximum error of less than 0.5 percent. The results shown in Table A2.1 were indirectly validated through the application of Eq. 3, which allows the determination of total growth time (T) on the basis of the food conversion ratio (FCR), and the feeding rate (FR) taken from industry tables (Stead and Laird, 2002).

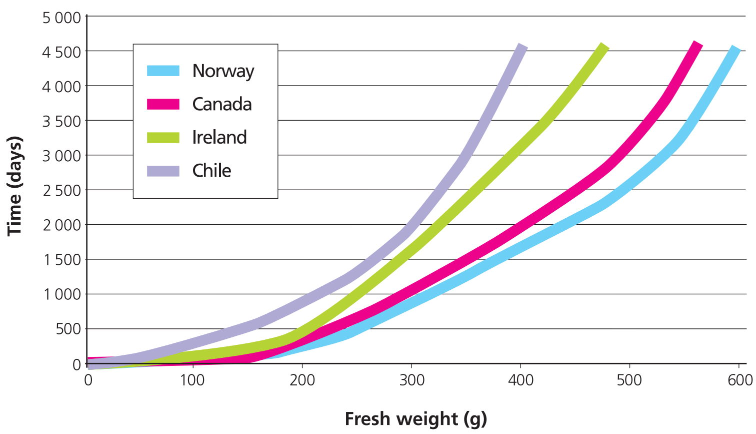
(Eq. 3) $$T = \frac{FCR\ (\ln end\ weight - \ln start\ weight)}{FR} * 100$$

T for the Norwegian sites (mean temperature = 8.5 °C) equates to an FR value of 0.9 to 0.8 (as percent body weight day^{-1}) for a 1 500 g fish, which, using the mean FCR from Table A2.1, gives a value for T of 547–616 days. A similar test for the Republic of Chile farms, with an FR value of 1.05 (mean SST: 11.9oC) gives T = 469 days.

The faster growth (Figure A2.2) is reflected in a higher mean specific growth rate in the Republic of Chile. The thermal growth coefficient (TGC) depends on both the temperature profile and duration of growth, as it uses the integral of daily temperatures over the cultivation period. The TGC is roughly identical for all regions except for the Kingdom of Norway, where it is roughly 10 percent higher, suggesting a better use of thermal energy. However, because this is an externality, there does not seem to be a particular advantage from this higher value. In any case, Stigebrandt (1999) notes that TGC will not be constant for the range of temperatures observed in Norwegian waters and that the TGC model should therefore be used with great caution.

The FCR is identical at all sites, and is typical of salmon aquaculture. Although FCR is usually expressed as a ratio of dry food mass to wet animal weight, Table A2.1 also presents these data in equivalent dry weight units, indicating that the fish production is around 30 percent of the total feed. Data for environmental variables integrated over the culture period are shown in the last four rows of Table A2.1. The values are essentially identical, which would be expected given the use of a target weight as the simulation endpoint. However a shorter production period has a potentially greater impact on the environment, as the rate of biodeposition, excretion of ammonia or oxygen consumption is higher. This needs to be considered in the light of higher SST, which additionally reduces the solubility of oxygen and promotes higher benthic metabolism, thus exacerbating negative impacts of cultivation. For the shortest cultivation period (the Republic of Chile), a single fish in a 1 m^3 volume consumes about 5 mg L^{-1} of dissolved oxygen (DO) per day, which requires an appropriate throughput of DO to successfully support cage culture.

FIGURE A2.2
Growth profiles at selected farms from each geographic area



Discussion

At first glance, the results are striking. They show an approximate five-month difference in the time required to reach a harvestable size between the Republic of Chile and the Kingdom of Norway. That would translate into a sizeable difference yield and in potential gross sales based on the (apparent) same capital investment in culture facilities between these locations. However, other factors such as effects of day length on feeding rates (e.g. Smith *et al.*, 1993) also have to be taken into account.

The inclusion of this salmon individual model in farm-scale models such as MOM (Ervik *et al.*, 1997; Stigebrandt, 1999) or FARM (Ferreira, Hawkins and Bricker, 2007; Ferreira *et al.*, 2009) allows such impacts to be examined at the appropriate scale of cultivation. FARM additionally provides a means to examine the environmental and production trade-offs of combining salmon and bivalve filter feeders, such as oysters or mussels, in integrated multitrophic aquaculture.

This simulation has already been carried out for other species, i.e. for combinations of gilthead bream and Pacific oyster, and required the development of a finfish model that addresses the growth response of fish to water current speed. Past a certain threshold, the metabolic costs of swimming (or opposing current in a moored cage) make aquaculture unviable. On the other hand, the simulated co-cultivation of fish and shellfish suggests that it is possible to use organic matter from finfish culture to cultivate shellfish in open ocean areas where the natural food supply would be insufficient for commercial growth.

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Annex 3

Remote sensing for the sustainable development of offshore mariculture

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Dean, A. & Salim, A. 2013. Remote sensing for the sustainable development of offshore mariculture. *In* J.M. Kapetsky, J. Aguilar-Manjarrez & J. Jenness. *A global assessment of offshore mariculture potential from a spatial perspective*, pp. 123–181. FAO Fisheries and Aquaculture Technical Paper N. 549. Rome, FAO. 181 pp.

ABSTRACT

Aquaculture is practised worldwide in highly variable environments. Many of the environmental factors that influence the sustainable development of aquaculture can be measured by remote sensing. Over recent decades, satellite remote sensing has supported the systematic, routine measurement of the seas, oceans, inland waters, and atmosphere. Recent advances in remote sensing systems, communications technology and computer processing mean that remote sensing products are more accessible and that these products will prove useful for offshore mariculture applications.

Information about the safety of aquaculture structures can be provided from processed satellite radar altimetry and coastal high-frequency radar. Several important information requirements related to a healthy environment for the growth and well-being of cultured organisms can also be met through remote sensing, including sea surface temperature, primary productivity and turbidity. However, some applications demand higher spatial resolution image products, or more frequent delivery than those operationally provided by different national and international agencies or organizations. For some products, cloud cover can limit the frequency of data acquisition.

There are three main applications of remote sensing for offshore aquaculture: (i) global and regional "suitability assessment" can integrate remote sensing data for analysis within geographic information systems (GIS) with data sets such as bathymetry, accessibility (distance to ports), and political and management information; (ii) "site selection and zoning" requires higher spatial resolution imagery products and several freely available data sets that can support activities that include chlorophyll-*a* concentration, turbidity and sea surface temperature. Currents, waves and winds are highly variable, and access to data requires engaging with commercial suppliers of satellite-derived data or a regional agency managing coastal high-frequency radar; and (iii) "monitoring" applications for offshore mariculture usually demand frequent observations and information reports on the environmental status (e.g. currents or chlorophyll-*a* concentration).

Remote sensing plays an important role in planning and management activities,

as does monitoring. The unique capability of satellite remote sensing to provide regular, repeated observations of the entire globe or specific regions at different spatial scales will also become increasingly important in the context of global climate change and the ecosystem approach to aquaculture.

With the proliferation of the technology, the range of satellite remote sensing data and information products available can be overwhelming. Many potential users of remote sensing data lack access to training, support, and tools to acquire and use data sets to support their activities. This review provides guidance to acquire data and begin to process data for incorporation into further analysis using GIS. The review points potential users to software and support available, and provides some demonstration remote sensing products and case studies at global and regional levels of relevance to offshore mariculture.

Contents

Tables

Figures

Acknowledgements

The authors are greatly indebted to all who assisted in the implementation and completion of this study by providing information, and advice.

The provisions made by ACRI-ST InfoceanDesk environment monitoring service from EU FP7 and ESA MyOcean GlobColour Products, ESA ENVISAT MERIS data, NASA MODIS and SeaWiFS data, acquired according to the authors specifications, greatly facilitated the work and is greatly appreciated.

Thanks are also due to Giuliana Profeti (Remote sensing and GIS expert, Florence, Italy), José Aguilar-Manjarrez (FAO Aquaculture Branch, Rome, Italy) and James McDaid Kapetsky (FAO consultant, Wilmington, North Carolina, United States of America) for their critical review of the manuscript. Maria Giannini (FAO consultant, Rome, Italy) is acknowledged for proofreading the document, and Marianne Guyonnet (FAO Statistics and Information Branch, Rome, Italy) for supervising its publication.

Abbreviations and acronyms

AATSR	Advanced Along-Track Scanning Radiometer
ACRI-ST	Observation de la Terre-Environnement (R&D company, France)
API	application programming interface
ASAR	Advanced Synthetic Aperture Radar
ATSR	Along-Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
AVISO	Archiving, Validation and Interpretation of Satellite Oceanographic data
CAP	Chile Aquaculture Project
CCRS	Canada Centre for Remote Sensing
CHL	chlorophyll
CNES	Centre national d'études spatiales (French Space Agency)
CZCS	Coastal Zone Color Scanner
DO	dissolved oxygen
EAA	Ecosystem approach to aquaculture
EEZ	exclusive economic zone
EOS	Earth Observing System (NASA)
ERS	Earth Resources Satellite
ESA	European Space Agency
ESRI	Environmental Systems Research Institute
FAO	Food and Agriculture Organization of the United Nations
GEOSAT	Geodetic Satellite
GHRSST	Group for High-Resolution Sea Surface Temperature
GIS	geographic information systems
GOES	Geostationary Orbiting Earth Satellites
HAB	harmful algal bloom
HDF	Hierarchical Data Format
HF	high-frequency (radar)
HYCOM	HYbrid Coordinate Ocean Model
IOCCG	International Ocean Colour Coordinating Group
KML	Keyhole Markup Language (for Google Earth or Maps)
MERIS	Medium Resolution Imaging Spectrometer
MESH	Mapping European Seabed Habitats
MGET	Marine Geospatial Ecology Tools
MODIS	Moderate Resolution Imaging Spectroradiometer
MPA	marine protected areas
m/s	metres per second
NASA	National Aeronautics and Space Administration
NASO	National Aquaculture Sector Overview
NEST	Next ESA SAR Toolbox
netCDF	Network Common Data Form
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NRT	near real-time
SAR	synthetic aperture radar
SeaWiFS	Sea-viewing Wide Field-of-View Sensor

SMOS	Soil Moisture and Ocean Salinity satellite
SST	sea surface temperature
SWH	significant wave height
TIROS	Television Infrared Observation Satellite
TSM	total suspended matter
WCS	Web Coverage Service
WFS	Web Feature Service
WMS	Web Map Service

1. Introduction

1.1 Objectives and overview

Aquaculture is practised worldwide in highly variable environments. Many of the environmental factors that influence the sustainable development of aquaculture can be measured by remote sensing. As such, remote sensing provides several essential elements to support the implementation of the ecosystem approach to aquaculture (EAA).11 The planning and implementation of the EAA requires explicit consideration of spatial information about ecosystem components and properties, and recent advances in remote sensing have greatly enhanced our ability to describe and understand natural resources, facilitate planning of aquaculture development, and support environmental impact assessments and monitoring. Satellites enable a unique synoptic view of the seas and oceans and regular repeated observations of the entire globe and specific regions. Satellite earth observation systems provide a range of observation data that complement and extend data available from in situ oceanographic sensors (e.g. buoys and ships). Operational oceanography data and information products of relevance to offshore mariculture, derived wholly or partly from remote sensing, include sea surface temperature (SST), primary productivity, ocean winds, currents12, salinity and wave heights.

The build-up of long time-series of data and advances in data processing mean that series of daily, weekly, monthly, annual and seasonal data are now available for many products, which are known as "climatologies". Ocean productivity and temperature data provided from remote sensing are important for the development of coupled atmosphere-ocean global circulation models. These data sets have made a large contribution to the scientific understanding of the Earth's ocean-climate system for climate change research and the prediction of its impacts. The relationship between climate change and ocean primary production is likely to be a key determinant of fish and fisheries production (Cushing, 1982; Forget, Stuart and Platt, 2009). In the realm of mariculture, climate change will affect where development can take place.

Advances in information and communications technology mean that potential users have timely and open access to these global and regional oceanographic data and information products. However, the range of satellite remote sensing data and information products available is sometimes overwhelming, especially to a non-remote sensing specialist. The aim of this review is to provide support to potential users who are active in offshore mariculture development on the application of remote sensing.

1.2 Offshore mariculture

The great diversity of coastal waters, including their topography, exposure (hydrodynamic energy) and depths, makes it difficult to define the conditions typical for offshore mariculture, and attempts to do this must be seen as preliminary approaches rather than absolute. As a premise for the further discussion, the Food and Agriculture Organization of the United Nations (FAO) has established general criteria for mariculture activities in three categories: coastal mariculture, off-the-coast

[11] The EAA is a "strategy for the integration of the activity within the wider ecosystem such that it promotes sustainable development, equity and resilience of interlinked social-ecological systems." (FAO, 2010; Aguilar-Manjarrez, Kapetsky and Soto, 2010).

[12] Geostrophic currents can be measured. Unlike surface currents caused by wind and tides, geostrophic current is the horizontal movement of surface water arising from a balance between the pressure gradient force and the Coriolis force (http://oceanmotion.org/html/background/geostrophic-flow.htm).

mariculture and offshore mariculture. These are mainly based according to the distance from the coast and water depth (revealing the degree of exposure), but also according to the operational requirements and accessibility to the farms in rough weather (Table A3.1).

TABLE A3.1
General criteria for coastal, off-the-coast and offshore aquaculture based on some environment and hydrographic characteristics

	Coastal	Off-the-coast	Offshore
Location/ hydrography	• < 500 m from the coast • ≤10 m depth at low tide • Within sight • Usually sheltered	• 500 m–3 km from the coast • 10–50 m depth at low tide • Often within sight • Somewhat sheltered	• > 2 km, generally within continental shelf zones, possibly open ocean • > 50 m depth
Environment	• Hs usually < 1 m • Short period winds • Localized coastal currents, possibly strong tidal streams	• Hs < 3–4 m • Localized coastal currents, some tidal streams	• Hs 5 m or more, regularly 2–3 m • Oceanic swells • Variable wind periods • Possibly less localized current effect
Access	• 100% accessible • Landing possible at all times	• > 90% accessible on at least once daily basis • Landing usually possible	• Usually > 80% accessible • Landing may be possible, periodic, e.g. every 3–10 days
Operation	• Regular, manual involvement, feeding, monitoring, and more	• Some automated operations, e.g. feeding, monitoring, and more	• Remote operations, automated feeding, distance monitoring, system function

Note: Hs = significant wave height – a standard oceanographic term, approximately equal to the average of the highest one-third of the waves.

Source: Lovatelli, Aguilar-Manjarrez and Soto (forthcoming).

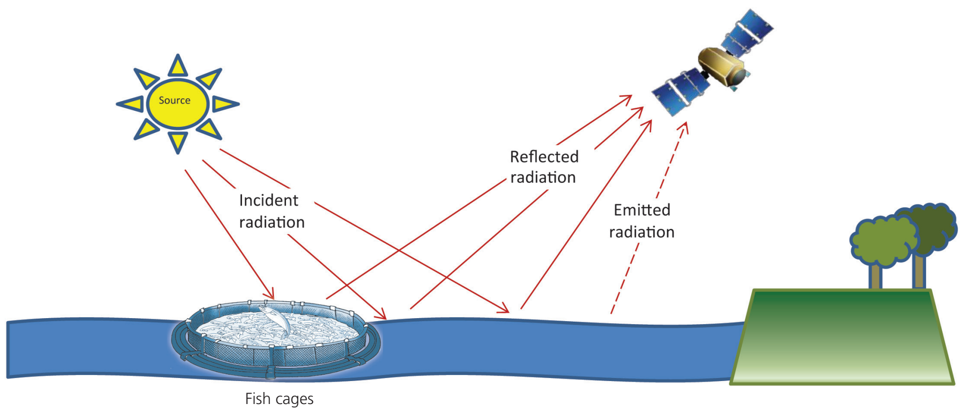
The use of the criteria in Table A3.1 calls for a careful approach because the term “offshore” could be understood differently by different people and because offshore locations according to the above criteria could be in internal waters in some countries with extensive archipelagos and in international waters in other countries.

The criteria can only give a preliminary idea of the farming conditions. Each national situation and prevailing local conditions at the sites should always be considered individually. Another way of defining mariculture locations, not shown in Table A3.1, is “sheltered” for coastal mariculture; “partly exposed” (e.g. > 90° open) for off-the-coast mariculture; and “exposed” (open sea, e.g. > 180° open) for offshore mariculture. For estimating offshore mariculture potential, Kapetsky, Aguilar-Manjarrez and Jenness (this publication) adopted a simplified definition of offshore aquaculture by Drumm (2010). Drumm’s (op. cit.) definition calls attention to open sea areas, significant exposure and severe sea conditions. The distance from the shore or safe harbour may or may not be a factor.

1.3 What is remote sensing?

Remote sensing is defined as “the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation” (Lillesand, Kiefer and Chipman, 2007). Remote sensing devices are sensors mounted on satellites and aircrafts, or installed at fixed coastal locations, that can measure the electromagnetic energy that is emitted or reflected by the features of the Earth’s surface. Remote sensing data are usually presented as an image comprised of a regular grid of picture elements, or pixels, which can then be displayed on a computer screen using specialized software or common applications such as Google Earth.

FIGURE A3.1
Overview of the process of remote sensing



The process of remote sensing is illustrated in Figure A3.1. The source of energy or illumination is usually the sun, but for radar sensors the radar energy is generated by the radar antenna. The energy source travels through the atmosphere and interacts with the target (e.g. ocean or ground surface). The reflected or emitted radiation is received by the remote sensor and converted into a signal that can be recorded and displayed as either numerical data or as an image.

For a recent and detailed review on remote sensing applications to fisheries and aquaculture, see Dean and Populus (2013). The remote sensing review describes the basics of remote sensing and its main applications to support fisheries and aquaculture management. It provides practical guidance for planning and implementing the use of remote sensing, including data selection and acquisition, image processing and the integration of images, within geographic information systems (GIS), and also includes case studies to illustrate how remote sensing has been applied to support coastal aquaculture mapping and sensitive habitat mapping, monitoring development of potentially harmful ocean conditions, and the identification of potential fishing grounds.

1.4 Main types of remote sensing data

The main types of remote sensing data can be classified into optical imagery and radar:

- **Optical images** – optical sensors (like our eyes) measure electromagnetic radiation in the visible blue, green and red wavelengths as well as infrared wavelengths (that human eyes do not detect). The source of energy for optical remote sensing is the sun, and the sensors measure reflected and emitted solar energy. Optical images can be interpreted intuitively by users; examples of data and information products include ocean chlorophyll-*a* concentration and photo-like images such as fish cages. In cloudy regions, it may not be possible to acquire imagery as often as needed or desired because optical wavelengths do not penetrate through clouds. Thermal imaging is a special case of optical imaging in which the measured energy is emitted by the Earth and is related to the temperature of the emitting surfaces; an example of thermal measurement is SST.
- **Radar** – operate in longer wavelengths (microwaves) and are not affected by cloud cover; radar data, however, are more challenging to interpret than optical imagery. Radar data are usually processed by a specialist or organization into a product that can be more easily used by a fisheries and aquaculture specialist. There are three types of radar that are of interest for offshore mariculture:

- **Imaging radar.** Presented as images, but containing different information compared with optical images, such as the sea surface roughness. Radar images can also provide clear identification of ocean surface structures such as fish cages or shellfish longlines.
- **Radar altimetry.** Complex data processing is conducted to provide information on surface currents, wave heights and wind speed.

- **High-frequency (HF) radar** – requires that radar stations are installed along the coastline in the area to be monitored. HF radar provides estimates of surface current direction and speed, as well as wave heights, within a specific area.

1.5 Key characteristics of remote sensing data

There is unprecedented availability of global and regional oceanographic data and information products. Many of the data and information products come from satellite remote sensing. The number and variety of products is huge, with products presenting numerous parameters with different temporal and spatial resolutions. In order to select available products, the user needs to consider the following:

- **Parameter** – defines what is being measured by the satellite sensor and/or derived using models, complementary in situ data, or other remote sensing data. The accuracy and precision of the measurements are obviously important.
- **Spatial extent** – remote sensing can be applied at a range of scales, such as global, regional and local areas.
- **Spatial resolution** – there are technical definitions of spatial resolution, but, as remote sensing data are usually processed into an image format, it is sufficient to understand that spatial resolution is the size of the individual pixel recorded by the sensor. Depending on the application, "low resolution" might be 20 m and "high resolution" might be 0.5 m (e.g. aquaculture structure mapping), or "low resolution" may be 50 km and "high resolution" might be 1 km (e.g. chlorophyll-*a* concentration). Users often desire high-resolution satellite data, but for large areas compromise is often needed because data may be too expensive to acquire and data volumes impractical to process. The spatial resolution of the product has an important impact on whether the product can describe geographic variability or patterns in enough detail (and at the desired time steps at a given level of resolution) for the intended application. For example, an available regional surface currents data set may be too coarse to describe local surface currents that are influenced by tides, which are of interest to a farm manager.
- **Revisit frequency** – defines the frequency of observations that can be made of the same area, which for satellite remote sensing depends on the satellite orbit and the extent and spatial resolution of the system. Data and information acquired for global studies are typically less detailed (relatively coarse) compared with those acquired for specific areas; however, they can be acquired more frequently. Cloud cover also affects the revisit potential of optical systems. While many sensors claim frequent revisit, their capacity to cover large areas may be limited. Some satellite sensors can "look" to the side of their orbit to provide more frequent coverage, but in most cases vertical observations are better for accurate, detailed mapping. Constellations of two or more of the same or compatible satellites can improve the revisit frequency.
- **Time series** – the time period over which consistent observations are available, usually referring to the historical period. Future continuity of data supply from a particular sensor, or a group of sensors with similar properties, may be important to ensure that frequent, ongoing information will be available to support the user's information needs.

- **Timeliness** – the speed that a product is made available to a user. Near real-time (NRT) products are designed to be delivered as quickly as possible (www.eurogoos.org), and are often called “nowcast” by oceanographers. Historical time series (“hindcast” or “offline”) products can be developed over long periods and are delivered only after careful compilation and calibration. It is also possible for remote sensing data to be incorporated into models to forecast ocean conditions. The timeliness of a product may also depend on the amount of processing required.
- **Product or data level** – a common challenge for a non-remote sensing specialist is that most data suppliers also refer to available “data levels”, which describe the amount of processing that the data supplier has conducted before the product is made available to the user. The simplest approach for non-specialists is to start with the higher level data (i.e. Level 3) because they are most likely to be products that can be directly integrated within a GIS and used for analysis. Data levels can be summarized as follows:
  - Level 1A: unprocessed instrument data at full resolution.
  - Level 1B: instrument calibrations have been applied to Level 1A data to provide more consistent values.
  - Level 2: derived variables at the same resolution as the source Level 1 data, e.g. SST data, where the spatial resolution of the data may vary across the image.
  - Level 3: derived variables in a regular grid formation, e.g. a regular grid of SST data. Level 3 data are sometimes called “binned” because they have a regular grid, or “mapped” if they have been map projected.

2. Data and information requirements

2.1 General requirements

There are several potential user groups of oceanographic remote sensing, and their data requirements differ partly based on the extent of their mandate or interest. From a global perspective, organizations such as FAO are exploring the use of GIS and remote sensing for estimating the potential for offshore mariculture in order to encourage countries with large absolute or relative potentials to undertake national-level studies, to improve the definition of that potential as a step towards updating policy on offshore mariculture, and to improve planning for aquaculture development. At a national or regional level, fisheries and aquaculture regulators and marine spatial planners also represent a potential user group, with data needed to support management of competing uses of the marine environment in a management zone or exclusive economic zone (EEZ). At a local level (and sometimes regional level), aquaculture developers and operators are interested in selecting the most suitable sites for aquaculture operations and in monitoring the environment.

Based on these broad groups of users and the spatial extent and resolution of their data and information requirements, there are three main potential applications of remote sensing for offshore mariculture:

- **Global and regional suitability assessment** – to contribute biophysical information to a process to determine the broad areas with potential for the culture of different species and their associated culture systems.
- **Zoning and local site selection** – to define marine zones and local areas that are appropriate for offshore mariculture development, within areas considered broadly suitable for different species and culture systems.
- **Monitoring** – to monitor the marine environment of operational farms, including local conditions and the marine zone, that may influence cultured species.

Data and information requirements can also be presented thematically, focusing on parameters of interest to users. Thematic requirements are broadly similar for fish, shellfish and marine plant aquaculture, but some parameters are more or less important for different cultured species. The subsections below provide more detail on the above potential applications and thematic data and information requirements.

2.2 Global and regional suitability assessment requirements

Much of the data required for spatially detailed and comprehensive analyses for zoning and siting of offshore mariculture is available only at national and subnational levels. Collection, compilation and spatial analysis of national and subnational data sets to estimate offshore mariculture potential at global and regional levels would be time consuming and expensive. However, there are spatial data sets useful for global and regional assessments of aquaculture potential. These data sets have two characteristics. The first characteristic is that the resolution is coarse, ranging from 1 km for marine bathymetry and up to 2 degrees for significant wave height. Estimations of mariculture potential are based on long-term data sets. Thus, the second characteristic is that the time-variable data must be organized into climatologies to enable analyses. Climatologies are compilations of time-variable data collected at relatively short time intervals with the observations organized into time steps that range from daily to monthly and annual compilations. Climatologies describe the short-term observations in terms of means, standard deviations and sample size for each time step. The longer the duration of the climatology, the better the coverage of seasonal and interannual variability.

Assessments of mariculture potential at global and regional levels focus on the most fundamental requirements for mariculture development. Basically, at global and regional levels, assessments of mariculture potential consider environments suitable for the culture systems (e.g. depths and current speeds for sea cages), environments that favour grow-out of cultured organisms (e.g. water temperature, food availability as chlorophyll-*a* for filter feeders), cost-distance from onshore support to offshore culture installations, and competing, conflicting and complementary uses of marine space (e.g. marine protected areas, navigation lanes).

Site suitability assessments require long-term data sets (historical data) that will provide a description of past environmental conditions and time series showing trends and changes (EuroGOOS; www.eurogoos.org). These data and their sources are described in the following sections.

2.3 Zoning and site selection requirements

Zoning and aquaculture site selection is the process of identifying and characterizing the most promising locations for offshore aquaculture.

The process may begin by considering a large area (potentially the whole EEZ), and systematically narrowing down the options into zones on the basis of different parameters, and ending finally to a smaller area for a detailed "siting study". The zoning and site selection process requires a range of different data and information, including socio-economic, political, legal and planning data, and may be part of a broad marine spatial planning process (Ehler and Douvere, 2007), or it may be focused on regional spatial planning for fisheries and aquaculture (FAO/Regional Commission for Fisheries, 2011).

Zoning and site selection requires data that are relatively detailed and that have more frequent observations compared with a suitability assessment. Historical data are required, which can be inputs for analysis and ecological modelling and model verification. Ireland provides an example of national zoning and site selection for offshore aquaculture development. The "offshore aquaculture development in Ireland" study (Watson and Drumm, 2007) implemented a process to survey all of Ireland's potential sites, which were narrowed down based on analysis of water depth, shelter, and proximity to landing facilities.

2.4 Monitoring requirements

Monitoring existing farms or marine areas typically needs NRT data, which may be compared with baselines from long-term averages. NRT data must provide the "most usefully accurate description of the present state of the sea, including living resources" (EuroGOOS, 2011; www.eurogoos.org). NRT delivery typically means a user has access to data and information products within a few hours to 24 hours. Based on integrated data within models, forecasts may provide predictions of the future condition of the sea and the air masses just above it. An important area for remote sensing monitoring is the mapping and prediction of potentially harmful algal blooms (HABs).

HAB (also called a red tide) may cause harm through the production of toxins or by their accumulated biomass, which can affect co-occurring organisms and alter food-web dynamics. Impacts include human illness and mortality following the consumption of, or indirect exposure, to HAB toxins, substantial economic losses to coastal communities and commercial fisheries, and HAB-associated fish, bird and mammal mortalities. "To the human eye, blooms can appear greenish, brown, and even reddish-orange depending upon the algal species, the aquatic ecosystem, and the concentration of the organisms" (www.whoi.edu/redtide).

An exception to the NRT monitoring is the monitoring and inventory of aquaculture structures, which would typically be required on an annual basis by the regulator of the industry.

2.5 Thematic data requirements

For each of the application areas described above, it is useful to categorize data and information requirements according to the parameters that impact fish, shellfish and marine plant cultivation: (i) environments where it is technically feasible and economically advantageous to place offshore culture installations and onshore support facilities; and (ii) environments that promote fast growth and high survival rates of cultured organisms.

Requirements can include long-term averages and variability, as well as NRT delivery of data and information and forecasts of future conditions.

2.5.1 Physical parameters for siting culture systems

- **Currents** – in this context, the reference is to ocean surface currents that are wind or tidal driven. Suitability assessment and site selection for offshore mariculture needs long-term historical information on the strength and variability of currents because currents disperse aquaculture wastes and possibly lessen the prevalence of certain ectoparasite infections; however, currents that are too strong can impact the safety of the installation and the cost of marine transport and access and servicing of the facilities, as well as the cultured organisms themselves (e.g. energy expended on swimming rather than growth).
- **Wind** – in this context, average wind speed. Suitability assessment and site selection for offshore mariculture may benefit from long-term information on the exposure of an area to strong winds and storms given the impact on wave heights and currents. There is also a direct wind effect on service boat operations apart from wave height. Monitoring for warnings and forecasts regarding the expected track and severity of storms may also be useful.
- **Wave height** – is technically defined as the difference in elevation between the crest of an ocean wave and the neighbouring trough; significant wave height (SWH) is a commonly used measure and is the average height of the one-third largest waves. Suitability assessment and site selection for marine aquaculture needs long-term information on SWH because of its importance for cost-effective and robust engineering of the marine aquaculture structures.

Table A3.2 Provides a summary of technical data and information needs for offshore mariculture.

TABLE A3.2

Environmental parameters where it is technically feasible and economically advantageous to place offshore culture installations and onshore support facilities

	Zoning (hindcast) and site selection		Monitoring (near real-time and forecast)
	Global/regional scale	Local scale	
Currents	Fish, shellfish and plants: • Multi-year averages and seasonal variability • 4 km resolution	Fish, shellfish and plants: • Multi-year averages and seasonal variability • 500 m resolution	Fish, shellfish and plants: • Hourly measurements • 7-day forecasts • 500 m resolution
Winds	Fish, shellfish and plants: • Multi-year averages and seasonal variability • 4 km resolution	Fish, shellfish and plants: • Multi-year averages and seasonal variability • 1 km resolution	Fish, shellfish and plants: • Hourly measurements • 7-day forecasts • 1 km resolution
Wave heights	Fish, shellfish and plants: • Multi-year averages and seasonal variability • 4 km resolution	Fish, shellfish and plants: • Multi-year averages and seasonal variability • 1 km resolution	Fish, shellfish and plants: • 7-day forecasts • 1 km resolution

2.5.2 Environmental parameters that promote fast growth and high survival rates of cultured organisms

- **Temperature** – sea surface temperature (SST) is physically determined by the incidence of solar radiation, ocean circulation and the depth of the mixed layer, which is affected by upwelling, surface winds and bathymetry. Offshore mariculture requires data and information on sea temperatures because fish and shellfish growth rates (and survival) are affected by average temperature and temperature variability. SST is the temperature of the water close to the surface, or the ocean "skin", and SST data are most likely applicable for suitability assessment and monitoring, the latter because models of ocean productivity need temperature data.
- **Primary production** – is the production of organic compounds from carbon dioxide through the process of photosynthesis, primarily by microscopic algae. Net primary production accounts for losses to processes such as cellular respiration. Primary production is mostly determined by the availability of light and mineral nutrients, the latter being affected by stratification and mixing of the water column. Offshore mariculture requires data and information on the primary production of an area because shellfish are filter feeders that rely on sufficient concentration of food particles such as phytoplankton for their growth. Chlorophyll-*a* concentration products that remote sensing can support are suitability assessment, zoning and site selection, and monitoring. Fish farmers may be interested in historical data and monitoring extremes of primary production, which may be harmful to fish health through oxygen depletion or which produce toxic compounds.
- **Turbidity** – is a measure of the transparency of sea water. Turbidity can be affected by local and regional currents and waves, coastal erosion, bottom type, phytoplankton concentration and river plumes. Offshore mariculture requires data and information on turbidity of an area because high concentrations of inorganic suspended matter can negatively affect fish and shellfish growth and health. The primary interest would be historical data.
- **Salinity** – is a measure of dissolved salt content, and variations can result from rainfall, evaporation, river discharge and ice formation. Offshore mariculture needs to understand the variable levels of salinity because feeding, growth and survival of shellfish can be affected by low salinity. Freshwater river plume distribution is an important site section issue and the interest is in historical data.
- **Dissolved oxygen (DO)** – a relative measure of the amount of oxygen that is dissolved or carried in a given medium. Marine aquaculture needs to understand the typical levels of DO and the presence of "dead zones" (i.e. hypoxic [low oxygen] areas in the world's oceans) because hypoxia may have detrimental effects on fish oxygen consumption, physiology, feed intake, growth and well-being.

Table A3.3 provides a summary of the environmental data information needs for offshore mariculture.

TABLE A3.3

Environmental parameters that promote fast growth and high survival rates of cultured organisms

	Site suitability, zoning (hindcast) and site selection		Monitoring (near real-time)
	Global/regional scale	**Local scale**	
Temperature	Fish, shellfish and plants: • Multi-year averages and seasonal variability • 4 km resolution	Fish, shellfish and plants: • Local variability can be important based on species selection • 1 km resolution	Fish and shellfish: • Daily to hourly measurement to support modelling of primary production • 1 to 4 km resolution
Primary production*	Fish and shellfish: • Frequency of extremes (HABs) Shellfish: • Multi-year averages and seasonal variability • 4 km resolution	Fish and shellfish: • Frequency of extremes (HABs) Shellfish; • Multi-year averages and seasonal variability; • 1 km resolution	Fish and shellfish: • 7-day forecasts of extremes (HABs) Shellfish: • Daily to hourly measurements • In situ and 1 km resolution
Turbidity	Fish, shellfish and plants: • Multi-year averages and seasonal variability • 4 km resolution	Fish, shellfish and plants: • Multi-year averages and seasonal variability • 1 km resolution	Fish and shellfish: • Daily measurement • 1 km resolution
Dissolved oxygen**	Fish, shellfish and plants: • Frequency of DO extremes (HABs) • In situ only	Fish, shellfish and plants: • Frequency of DO extremes (HABs) • In situ only	Fish and shellfish: • Daily measurement of DO • In situ only
Salinity	Fish, shellfish and plants: • Multi-year averages and seasonal variability. • Identify freshwater river plumes • 4 km resolution	Fish, shellfish and plants: • Multi-year averages and seasonal variability • Identify freshwater river plumes • 1 km resolution	Fish, shellfish and plants: • Not important

Note: *Including phytoplankton species analysis. ** Depth profiles of parameters are ideally required.

3. Available remote sensing data products

The subsections below aim to provide a summary of the available remote sensing data products that are able to meet the thematic data and information needs described in the previous section.

3.1 Environmental parameters to place offshore culture installations and onshore support facilities

To establish if an area represents a safe environment for offshore mariculture requires information on surface currents, wave heights and winds. Satellite radar altimeter systems are capable of measuring sea surface height, from which ocean circulation patterns and sea level are determined on a global scale. Marine weather forecasts, which include wave height predictions, are based partly on satellite remote sensing and can be used for the installation and management of offshore mariculture. Altimetry data are also used to compute wave heights (e.g. SWH measured in metres) and wind velocity (metres per second [m/s]).

There has been an almost continuous series of radar altimetry missions since 1985, starting with GEOSAT, and measurements are currently continuing with JASON-1 (2001), Ocean Surface Topography Mission on JASON-2 (2008), and with Envisat (2002). Table A3.4 provides a summary of radar altimetry missions, and Table A3.5 lists the main sources of radar altimetry-based products.

TABLE A3.4

Summary of radar altimetry satellite missions

Satellite(s)	Operational period	Orbit
GEOSAT GEOSAT Follow-On	1985–1990 1998–2008	17-day repeat cycle
ERS-1 ERS-2 Envisat	1992–1996 1995–2011 2002 to present	35-day repeat cycle
Topex/Poseidon Jason-1 Jason-2	2001–2005 2001 to present 2008 to present	10-day repeat cycle

Source: http://earth.eo.esa.int/brat/html/missions/welcome_en.html

Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO) distributes free satellite altimetry data from Topex/Poseidon, Jason-1, ERS-1 and ERS-2, and Envisat in NRT on a daily basis. AVISO products include a 25-km spatial resolution “geostrophic current” product and a 90-km spatial resolution SWH and surface wind product. Satellite altimetry does not measure tidal currents, which are a result of the rise and fall of the water level due to tides. The effects of tidal currents on the movement of water in and out of bays and offshore can be substantial and more important than geostrophic currents for aquaculture development. To determine tidal currents requires oceanographic modelling, and it is not a product that can be delivered from remote sensing. The free AVISO data are delivered as NRT daily data and there are no long-term averages provided. The coarse resolution of the products may mean that they are only useful for global and regional suitability assessments for offshore mariculture. The AVISO SWH and wind data at 90-km resolution are used in this review in Chapter 5 “Demonstration products and case studies”.

The European Space Agency (ESA), with support from the French Space Agency (Centre national d'études spatiales), has established the GlobWave Project to provide satellite wave products to users around the globe. The project is ongoing and provides free access to satellite wave data and products in a common format, both historical and in NRT.

TABLE A3.5
Sources of radar altimetry products

Portal Name	Details	Access
AVISO	Geostrophic currents, SWH and surface winds.	www.aviso.oceanobs.com/en/data/products
GlobWave	Satellite wave data products (under development).	www.globwave.org
MyOcean	Provides access to a range of regional and global ocean data, including AVISO products.	www.myocean.eu.org
eoPortal	ASAR and ERS and others. Searchable online catalogue, particularly useful for searching ESA archives.	http://catalogues.eoportal.org
Ocean Watch	NASA, NOAA, AVISO surface currents and many other data. Preview and download various data, including for custom user specified regions.	http://las.pfeg.noaa.gov/oceanWatch

Coastal HF radar is another source for surface currents and wave height data, which provides higher spatial resolution data (e.g. 1 km) and on a more frequent and timely basis (e.g. real-time hourly data).

Of course, availability of HF radar data requires investment in radar stations along the coastline of interest. HF radar now cover increasingly large areas of the United States of America; for example, through the National Oceanic and Atmospheric Administration (NOAA) HF Radar National Server and Architecture Project (http://hfradar.ndbc.noaa.gov), which provides a demonstration of the HF radar display capability using Google Maps.

HF radar operates at long wavelengths (6 to 30 m) and requires two or more radars to be looking at the same area of water using two or more different viewing angles (www.codar.com/intro_hf_radar.shtml).

The complex radar processing allows precise information of the surface currents and wave heights. While providing timely data on the latest ocean currents and wave conditions, HF radar data are not archived to develop long-term climatologies.

A potential alternative source of currents data that is more suitable for offshore mariculture is the HYbrid Coordinate Ocean Model (HYCOM; www.hycom.org). The HYCOM consortium is a partnership of institutions that represent a broad spectrum of the oceanographic community, and it aims to meet a number of objectives, including the three-dimensional depiction of the ocean state at fine resolution in real-time and the provision of boundary conditions for coastal and regional models.

Data from HYCOM can be accessed by establishing an agreement with the consortium; its currents data may be more useful than freely available altimetry for global and regional suitability assessment and zoning and site selection.

A disadvantage is the need for processing of the available data into the appropriate depths and time steps that may be beyond desktop capabilities.

Another option for currents data is from MERCATOR-OCEAN (www.mercator-ocean.fr). The MERCATOR-OCEAN "observed ocean" system is based on altimetry and in situ data measurements. The satellite data sources include altimetry satellites and SST. In situ data are measurements taken at sea, including submerged sensors and drifting buoys fitted with a satellite positioning system. The spatial resolution of the global observed currents products and forecasts is 1/4 degree (~20 km).

3.2 Environments that promote fast growth and high survival rates of cultured organisms

To establish if an area represents a healthy environment for the growth and well-being of cultured organisms for offshore mariculture requires information on temperature, primary production, turbidity, salinity and DO. The importance of these different parameters varies according to the cultured species (fish, shellfish or plants).
Remote sensing can provide operational oceanographic data on SST, primary production, turbidity and, more recently, salinity at very coarse spatial scales. Information on DO cannot be provided from remote sensing.

3.2.1 Sea surface temperature

A summary of satellites and sensors relevant for SST observations is provided in Table A3.6. Since the late 1970s, SST measurements have been operationally available from the Advanced Very High Resolution Radiometer (AVHRR) sensors on the NOAA/TIROS meteorological satellites.

Other sensors include: the National Aeronautics and Space Administration's (NASA) Moderate Resolution Imaging Spectroradiometer (MODIS) sensors onboard the Earth Observing System AQUA and TERRA satellites; ATSR and AATSR from ESA missions; and NOAA's Geostationary Orbiting Earth Satellites (GOES) satellites that are geostationary over the Western Hemisphere.

TABLE A3.6
Summary of sea surface temperature-related optical remote sensing systems

Sensor	Satellite(s)	Operational period	Orbit/coverage	More Information
AVRR	NOAA 4 to 19 and TIROS METOP-A	1978 to present; 2007 to present	Polar orbit; 2 800 km swath; global coverage every day	www.oso.noaa.gov/poesstatus
MODIS	EOS TERRA EOS AQUA	1999 to present; 2002 to present	Polar orbit; 2 330 km swath; global coverage every one to two days	http://modis.gsfc.nasa.gov
Imager, Sounder	GOES 1 to 12	1975 to present	Geostationary; orbit Western Hemisphere	http://goes.gsfc.nasa.gov/
ATSR AATSR	ERS-1 and 2 Envisat	1991 to present; 2002 to present	500 km swath; global coverage every 3 days	http://envisat.esa.int/instruments/aatsr http://envisat.esa.int/handbooks/aatsr

Table A3.7 provides an overview of popular sources of SST data. The Group for High-Resolution Sea Surface Temperature (GHRSST: www.ghrsst.org) provides operational access to nearly all satellite SST data sets in a common format and within several hours of acquisition by the satellite instrument. GHRSST products (typically 10 to 50 km spatial resolution) are generated by combining complementary satellite and in situ observations. Several high spatial resolution (< 5 km resolution) regional SST analysis products are available; for example, from ESA for the Mediterranean (Medspiration project; http://projets.ifremer.fr/cersat/Information/Projects/MEDSPIRATION2).

Complementary to GHRSST, SST data products are also provided by national agencies that operate SST-related missions. The "4 km AVHRR Pathfinder Project" has produced a 4 km global coverage product using the AVHRR sensor series for the entire 1985–2001 time series. The 4 km AVHRR Pathfinder Project data are used in this review in Chapter 5 "Demonstration products and case studies".

TABLE A3.7

Sources of sea surface temperature data and information products

Source	Details	Access
NOAA	4 km AVHRR Pathfinder Project; 4 km global product provides long-term SST "climatologies", including mean, variance and anomalies.	www.nodc.noaa.gov/satellitedata/pathfinder4km
NASA	Aqua MODIS Seasonal Climatology Sea Surface Temperature.	http://oceancolor.gsfc.nasa.gov/cgi/l3
GHRSST	Level 4 gridded SST products (typically 10 to 50 km spatial resolution).	www.ghrsst.org
Rutgers University	AVHRR; real-time and archive SST daily composite for eastern United States of America, including the Gulf of Mexico.	http://marine.rutgers.edu/mrs/sat_data
MyOcean	Provides access to a range of regional and global SST data, including GHRSST.	www.myocean.eu.org

Note: Data levels are described in Section 1.5.

3.2.2 Primary production and turbidity

Ocean colour satellite sensors cover a specific range in the electromagnetic spectrum and can provide users with several derived parameters including chlorophyll-*a* concentration and turbidity (total suspended matter [TSM]). Chlorophyll-*a* concentration (mg/L) provides an estimate of the amount of chlorophyll-*a*-like pigments in the upper few centimetres of the water column and is related to primary production. TSM is a measure of turbidity and represents concentrations of suspended particulate matter (mg/L).

The optical properties of ocean waters have been used to define Case 1 and Case 2 waters (Mobley et al., 2004; Morel, 1988): Case 1 waters are those waters whose optical properties are determined primarily by phytoplankton and related coloured dissolved organic matter and detritus degradation products. Case 2 waters are everything else, namely waters whose optical properties are significantly influenced by other constituents such as mineral particles, coloured dissolved organic matter, or microbubbles, whose concentrations do not co-vary with the phytoplankton concentration. The distinction between Case 1 waters (usually coastal) and Case 2 waters (usually offshore) is important for application of algorithms used to process satellite remote sensing data.

A summary of satellites and sensors related to ocean colour observations is provided in Table A3.8. No single ocean colour sensor is capable of observing every part of the globe every day, so a combination of sensors is often used. Following the successful launch in 1978 of the Coastal Zone Color Scanner (CZCS), there have been several overlapping ocean colour satellite missions. Currently, SeaWiFS, MODIS, MERIS and others provide data to support operational oceanography products. There are also national missions such as Oceansat-1 (the Republic of India). The International Ocean Colour Coordinating Group (IOCCG) provides a good summary of the current and future availability of ocean colour sensors (www.ioccg.org/sensors_ioccg.html). Future sensors of particular interest are those onboard ESA's Sentinel 3 (launch 2013) and NOAA's NPP and NPOESS (2011 and 2014).

TABLE A3.8

Summary of ocean colour-related optical remote sensing systems

Sensor	Satellite(s)	Operational period	Orbit/coverage
SeaWiFS	OrbView-2	1997 to present	Polar orbit; 1 500 km swath
MODIS	EOS TERRA EOS AQUA	1999 to present 2002 to present	Polar orbit; 2 330 km swath; global coverage every one to two days
MERIS	Envisat	2002 to present	Polar orbit; 1 200 km swath
Ocean Colour Monitor (OCM) 1 and 2	Oceansat-1 and 2	1999 to present 2009 to present	1 400 km swath; global coverage every one to two days

Source: IOCCG (2009).

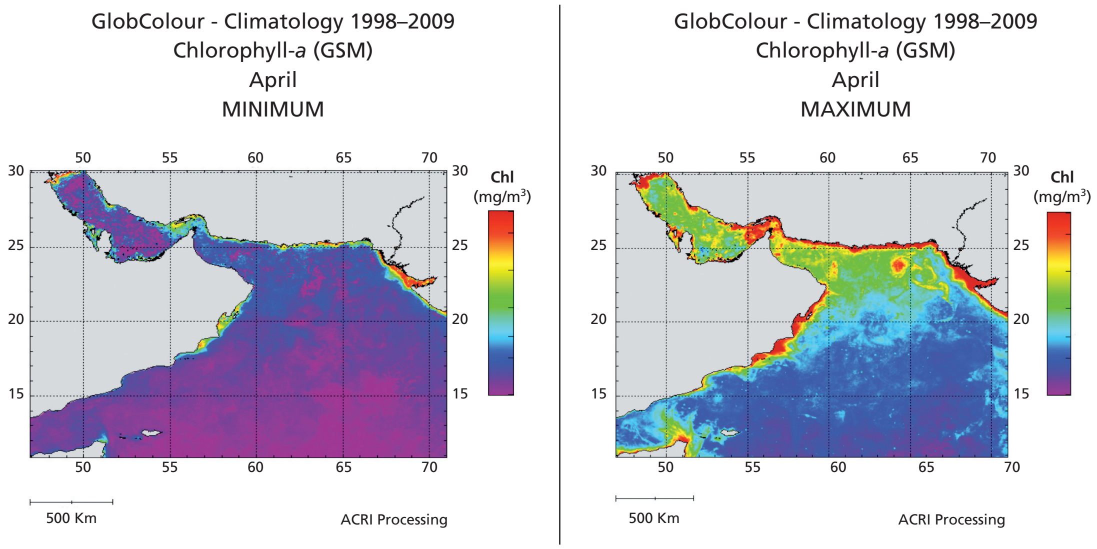
Table A3.9 provides an overview of popular sources of ocean colour data. The "ESA GlobColour" project has merged observations made with different satellite systems to enable global daily coverage. GlobColour provides time series from 1997 to the present of consistently calibrated and validated global ocean colour information with a 4.6 km spatial resolution coverage.

The ACRI-ST InfoceanDesk environment monitoring service has recently made available global and regional climatology products of chlorophyll-*a* concentration and TSM at 4.6 km and 1 km resolution. These climatology products are derived from EU FP7 and ESA MyOcean GlobColour Products, ESA ENVISAT MERIS data, NASA MODIS, and SeaWiFS data. Demonstration products include:

- Monthly average chlorophyll concentration (1998–2009);
- Maximum and minimum average monthly chlorophyll concentration (1998–2009);
- Monthly anomaly of average chlorophyll concentration (1998–2009). The anomaly is the relative difference of the data for a particular month with the average of all observations available during the months of the 1998–2009 period.

These products were added to FAO GeoNetwork: www.fao.org/geonetwork/ (simply search for "Chlorophyll Climatology"). An example product for the Gulf of Oman area is shown in Figure A3.2.

FIGURE A 3.2
Minimum and maximum and chlorophyll concentration in the Gulf of Oman area for the month of April for the period 1998 to 2009



Source: ACRI-st Infocean Desk.

The processing of more than a decade of historical satellite data to produce chlorophyll concentration climatology products provides valuable data for the aquaculture site selection process for new facilities. Analysis of the frequency and distribution of algal bloomww events may support spatial and temporal risk assessment. In Chapter 5, a pilot web-based harmful algal bloom warning system for the Chilean aquaculture sector is described, which used MERIS and MODIS remote sensing data; was an important demonstration that contributed to the establishment of the ACRI-ST InfoceanDesk.

TABLE A3.9

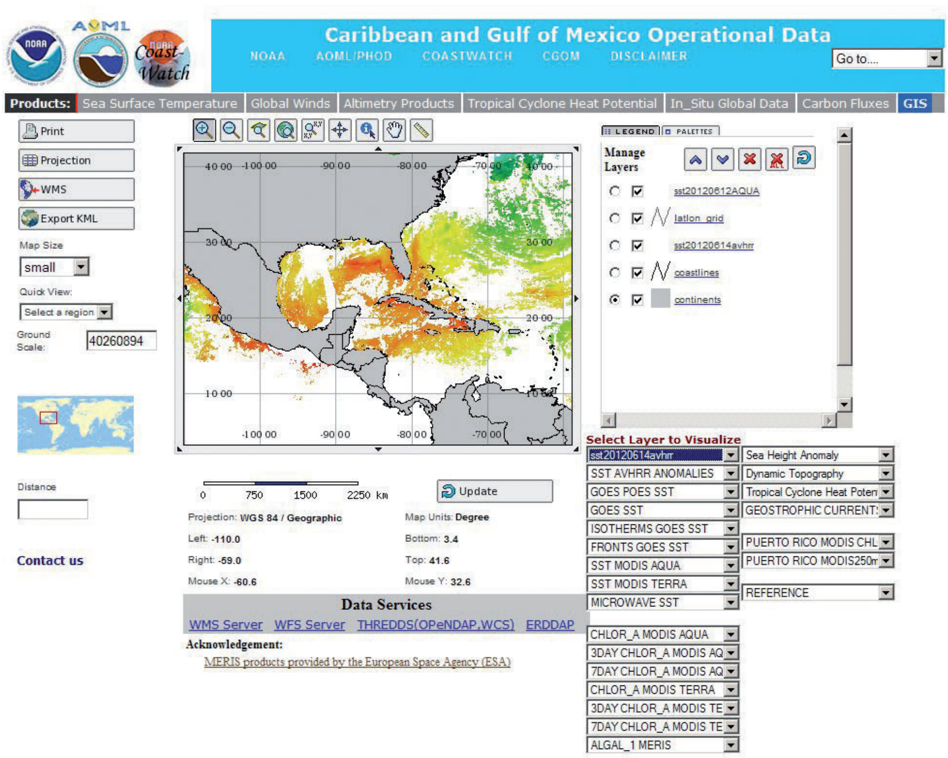
Sources of ocean colour data and information products

Source	Details	Access
InfoceanDesk	Merging of MERIS, SeaWiFS and MODIS Level 2 data; daily, weekly and monthly Level 3 products (15-day delay or daily NRT). Extraction of ocean colour data for user-defined areas is possible and a free GlobColour subscription service allows users to systematically obtain NRT products at 1 km spatial resolution of a specific area. The ACRI-ST InfoceanDesk environment monitoring service is known as "Pôle Mer" in France, and is partly funded by FUI and PACA region.	http://hermes.acri.fr
NASA Ocean Color Web	CZCS, SeaWiFS, and MODIS Level 1 to 3 data; daily, weekly, monthly and seasonal climatologies.	http://oceancolor.gsfc.nasa.gov
NOAA Coastwatch	Provides access to multiple satellite ocean remote sensing data and products for selected marine zones of the United States of America.	http://coastwatch.noaa.gov
MyOcean	MyOcean provides access to a range of information services. As part of MyOcean, the ACRI-ST Global Ocean Colour Processing Unit provides access to a range of regional and global ocean colour data, including GlobColour.	www.myocean.eu.org

Note: Data levels are described in Section 1.5.

The "NASA Ocean Color Web" provides access to CZCS, SeaWiFS and MODIS data in product levels from 1 to 3, including daily, weekly, monthly and seasonal climatologies. Other regional ocean colour services exist, including NOAA Coastwatch (see Figure A3.3).

FIGURE A3.3
NOAA Coastwatch Caribbean and Gulf of Mexico Web GIS of operational oceanographic data



Source: NOAA (2000), http://cwcgom.aoml.noaa.gov/cgom/webgis.phtml

3.2.3 Salinity

Passive satellite radar can detect the low levels of emitted microwave radiation from the Earth's surface.

Launched in 2011, the joint Argentine Republic and the United States of America Aquarius satellite will provide monthly maps of global changes in ocean surface salinity with a resolution of 150 km, showing how salinity changes from month to month, season to season, and year to year at a global scale. (www.nasa.gov/mission_pages/aquarius/news/aquarius20110922.html).

In 2010, ESA launched the Soil Moisture and Ocean Salinity (SMOS) satellite, which carries the Microwave Imaging Radiometer with Aperture Synthesis (MIRAS) passive microwave instrument (www.esa.int/esaLP/ESAL3B2VMOC_LPsmos_0.html).
It had one objective: to provide salinity measurements. SMOS data are intended to be used for global climate change research and have a coarse spatial resolution of 40 km; however, the salinity measurements are expected to be averaged over areas of 200 × 200 km (ESA, 2009), and so they will not likely be useful for offshore mariculture applications. More information on SMOS is provided at the European Space Agency[13].

3.3 Competing and conflicting uses

Remote sensing may also support the identification of locations that will conflict with other uses, and identify areas where there may be advantages of possible complementary uses of adjacent space. As described by Kapetksy, Aguilar-Manjarrez and Jenness (this review), uses for offshore mariculture currently under discussion include marine protected areas (MPAs), wind-farm supporting structures, wave energy, and unused oil or gas platforms, which can all be detected and monitored by remote sensing.

MPAs would reduce the areas having potential for offshore mariculture; remote sensing has the potential to provide environmental indicators such as long-term average primary productivity and ocean temperatures that are relevant to the design of MPAs. Remote sensing may also help to exclude some other areas that are the most productive fishing grounds, or sensitive habitats, that may not be within an MPA (e.g. seagrass beds – see Section 5.5).

3.4 Summary

Satellite remote sensing has the potential to meet the data and information needs of a range of different applications for offshore mariculture, including global and regional suitability assessment, zoning and site selection, and monitoring.

Several thematic offshore mariculture data requirements can be addressed and Table A3.10 summarizes the recommended freely available data along with the temporal and spatial resolution. It is clear that the freely available remote sensing data have some limitations for aquaculture applications because of their spatial resolution, particularly the radar altimetry derived SWH and wind data. However, these products provide an excellent low-cost entry into the application of remote sensing for aquaculture applications in order to gain experience and understand the potential. After users conduct an initial study, they can contact the suppliers and establish the costs for customized regional data at higher spatial resolution.

[13] SMOS scientific objectives: www.esa.int/esaLP/ESAS7C2VMOC_LPsmos_0.html.

TABLE A3.10

Recommended freely available remote sensing data products

Parameter	Spatial resolution	Temporal resolution	Recommended source
Chlorophyll-*a* (mg/L)	1 km regional 4.6 km global	Daily NRT Offline/hindcast Climatology	ACRI-ST InfoceanDesk environment monitoring service
TSM (mg/L)	1 km regional 4.6 km global	Daily NRT Offline/hindcast Climatology	ACRI-ST InfoceanDesk environment monitoring service
SST (°C)	4 km global	Offline/hindcast Climatology	4 km AVHRR Pathfinder Project
	10–50 km global	Daily NRT	GHRSST
SWH (m)	90 km global	Daily NRT	AVISO
Winds (m/s)	90 km global	Daily NRT	AVISO
Currents (m/s)	25 km global	Daily NRT	AVISO
	1/12 degree (~8 km)	Offline/hindcast model	HYCOM consortium
	1/4 degree (~20 km)	NRT and forecast	MERCATOR-OCEAN

Note: TSM = total suspended matter; SST = sea surface temperature; SWH = significant wave height; NRT = near real-time.

Currently available chlorophyll-*a* concentration and SST data are suitable for offshore mariculture applications in terms of spatial resolution at a global scale. In coastal environments, 4 km and 1 km spatial resolution products may be affected by the reflectance from the land surface, especially if the coastline is characterized by many small islands and narrow inlets. The temporal resolution of products can be limited because of cloud cover and satellite orbit characteristics. The combination of multiple ocean colour sensors by the GlobColour project and ACRI-ST InfoceanDesk environment monitoring service is beneficial, and some monitoring applications such as algal blooms and seston depletion could be operational in the near future.

4. Tools and resources

Users may now be ready to explore remote sensing data for a particular application based on the information provided in the previous chapters. The sections that follow introduce resources (information sources, references, tools) for further information and technical support for remote sensing application for offshore mariculture.

4.1 Getting Started

It can be difficult to know how or where to begin using remote sensing data for offshore mariculture. Before starting, it is important to define what information or outcome is expected. To scope out what is available and what is possible, the following steps are recommended:

1. Define the ecosystem boundaries of a study area.
2. Identify the relevant issue(s) to address (e.g. suitability assessments, zoning and site selection, and/or monitoring).
3. Define the spatial scale (e.g. farm, watershed, region) and the temporal scales (i.e. time scales are relevant in addressing aquaculture strategies and planning).
4. Compare the data and information requirements with the FAO information resources and other information resources (see Sections 4.2 and 4.3).
5. Use different satellite imagery catalogues to determine if images are available for an area for free download or purchase, depending on the sensor (see Section 4.4). Choose from the different data formats (see Section 4.5), and consider the costs of data (see Section 4.6).
6. Select an appropriate software application, starting with the free or open source options (see Section 4.7). Some of the tools require more time and effort to learn. An application like Google Earth can be useful to gain an understanding of the geographic setting of an area.
7. Investigate if there are local or regional organizations with expertise in using remote sensing for marine applications, such as a university or government agency, to provide assistance.

4.2 FAO information resources

The FAO Fisheries and Aquaculture Resources Use and Conservation Division actively promotes the use of GIS, remote sensing and mapping for the analysis of fisheries and aquaculture data, and supports the development of sustainable fisheries and aquaculture. Two key sources of information of direct relevance to remote sensing are: (i) the GIS portal (GISFish); and (ii) the new National Aquaculture Sector Overview (NASO) maps collection Web site to inventory and monitor aquaculture.

GISFish (www.fao.org/fishery/gisfish/index.jsp). GISFish is a site from which to obtain the global experience on GIS, remote sensing and mapping as applied to fisheries and aquaculture. GISFish sets out the issues in fisheries and aquaculture, and demonstrates the benefits of using GIS, remote sensing and mapping to resolve them. The global experience provided by GISFish is captured in "Issues, Publications, Activities, Training, Data and Tools, Contacts, Discussions, News and Events". Using the "Data and Tools" menu of GISFish, access is gained to a wide range of fisheries and aquaculture associated data, including links to remote sensing data and tools. The FAO Aquaculture Branch has produced a series of fisheries technical publications on GIS since the early 1980s, which are readily available in GISFish. Among these publications, the technical papers by Meaden and Kapetsky (1991)[14] and Meaden and Do Chi (1996) stand out, from a practical viewpoint, as the most consulted GIS-related publications for fisheries and aquaculture from FAO to date.

A single technical manual for both sectors is currently in preparation to update the previous work, given that fisheries and aquaculture share a number of common spatial planning issues (e.g. data, models, training, experience) that require synergies that need to be strengthened for the future implementation of the ecosystem approach to aquaculture/ecosystem approach to fisheries and marine spatial planning approaches (Meaden and Aguilar-Manjarrez, 2013).

NASO maps (www.fao.org/fishery/naso-maps/en). An excellent starting point for a spatial inventory of aquaculture with attributes that include species, culture systems and production is the FAO NASO map collection. The collection consists of Google maps showing the location of aquaculture sites and their characteristics at an administrative level (state, province, district, etc.) and, in some cases, even at an individual farm level. The data presented depend on the degree of aquaculture development and the resources available for data collection and the level of clearance provided by each country. The information provided in NASO has been primarily provided by experts on aquaculture and by national authorities and supplemented by data collected/processed by FAO to illustrate reported production statistics.

The NASO maps Web site also illustrates a few "select aquaculture sites" (www.fao.org/fishery/naso-maps/selected-aquaculture-sites/jp). The sites have been selected by national experts and aim to illustrate: (i) a few examples of different culture systems, cultured species, environments (freshwater, brackish water and marine) and scales (local, waterbody and/or watershed); and (ii) the potential of remote sensing for operational management of aquaculture. In addition to the NASO maps Web site, Figure A3.4 illustrates some examples of imagery found in Google Earth of relevance to offshore mariculture, which are also available in the NASO map collection.

[14] Chapter 4 of Meaden and Kapetsky (1991) includes a chapter on remote sensing as a data source.

FIGURE A3.4
Selected off-the-coast mariculture sites in Google Earth

Penghu Island Taiwan Province of China. Cobia
Coordinates: 23°36′47.95″N, 119°31′29.24″E

Source/Imagery:
Image © Digital Globe
© 2012 Kingway Ltd.

Chile. Atlantic salmon
Coordinates: 43° 2′7.76″S, 73°26′42.97″W
Concession 6

Source/Imagery:
© 2012 Cnes/Spot image
Data SIO, NOAA, U.S., Navy, NGA, GEBCO
Image © 2012 Geoeye
Image © 2012 Terrametrics

Belize. Cobia
Coordinates: 17°18′28.05″N, 88° 9′57.91″W

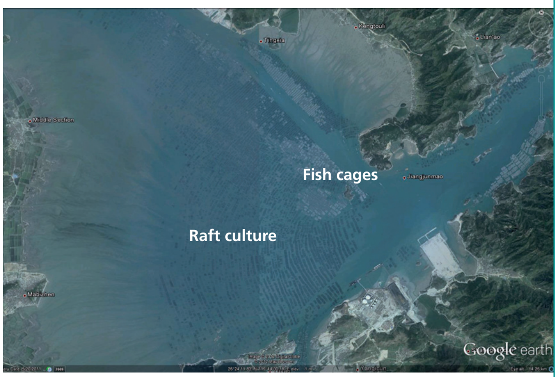
Source/Imagery:
Imagery: © 2012 Google, Image © 2012 Digital Globe

Norway. Atlantic salmon
Coordinates: 60°41′17.31″N, 4°44′4.73″E

Source/Imagery:
Image © 2012 DigitalGlobe
Image © 2012 GeoEye

Grand Manan Island, Canada. Atlantic salmon
Coordinates: 44°43′5.26″N, 66°43′53.03″W

Source/Imagery:
Image © 2012 GeoEye



China. Ningde, Fujian Province.
Dark colour is raft culture of Phorphyra (Nori).
Bright colour structures are for cage culture of marine fin fishes.
Coordinates: 26°24′9.58″N, 119°43′45.38″E

Source/Imagery:
Image © 2012 Terrametrics;
Image © 2012 DigitalGlobe;
© 2012 Mapabc.com

4.3 Other information resources

Canada Centre for Remote Sensing (CCRS; www.nrcan.gc.ca/earth-sciences/geography-boundary/remote-sensing/11810) – remote sensing outreach materials in English and French. Includes an excellent Glossary of Remote Sensing Terms.

Census of Marine Life (http://comlmaps.org/how-to/layers-and-resources) – has produced an excellent "Layers and Resources" section on its Web site, where there are simple instructions for data download and data conversion for many of the data sets described in Chapter 3 of this publication.

Global Marine Information System (http://amis.jrc.ec.europa.eu/index_fullscreen.php) – the European Commission Joint Research Centre developed this system to provide bio-physical information related to water quality assessment and resource monitoring in coastal and marine waters. The bulk of environmental analysis relies on continuous, detailed and accurate information on relevant marine biophysical parameters as derived from optical and infrared satellite sensors.

International Ocean-Colour Coordinating Group (IOCCG; www.ioccg.org) – is a useful resource to understand ocean colour data. The IOCCG has published several useful reports, including remote sensing in fisheries and aquaculture (Forget, Stuart and Platt, 2009), and conducts and sponsors advanced training courses on applications of ocean-colour data in various developing countries.

Mapping European Seabed Habitats (MESH; www.searchmesh.net/Default.aspx?page=1658) – habitat mapping is a process that ultimately generates a habitat map to meet a specific and clearly defined need. The MESH Guide describes each of the stages in the habitat mapping process, with the final chapter providing examples of how habitat maps have been used to solve real problems. MESH webGIS presents the seabed habitat maps produced by the MESH project, with supporting layers showing coastlines and administrative areas, physical data (e.g. bathymetry, seabed geology), biological sample data, and images of the seabed obtained from a vessel.

Mediterranean Operational Oceanography Network (www.moon-oceanforecasting.eu) – has an objective to consolidate and expand the Mediterranean Sea concerted monitoring and forecasting systems, and to ensure full integration to the overall operational oceanography global ocean European capacity. The "Services" page lists a number of European ocean monitoring and forecasting services.

SAFARI Project (Societal Applications in Fisheries and Aquaculture using Remotely-Sensed Imagery; www.geosafari.org) – the IOCCG co-sponsors the project, which was developed under the umbrella of the Group on Earth Observations (www.earthobservations.org). The SAFARI Project aims to accelerate the pace of assimilation of remote sensing data into fisheries research and ecosystem-based fisheries management on a world scale.

Tools for Marine Spatial Planning (www.ebmtools.org/msptools.html) – provides steps in the marine spatial planning process; Step 5 (Define and Analyze Existing Conditions) describes the role that remote sensing can play in marine spatial planning.

4.4 Data catalogues

Based on the objectives of a proposed project, suitable remote sensing data must be chosen from the available data; in some cases acquisition of new data may be required. There are a number of data catalogues for different sensors, which enable searches for data using parameters such as area of interest, date/time of acquisition, data type and spatial resolution.

Remote sensing experts may also want to check also other parameters, such as sensor angle, as images acquired looking straight down (vertical) are often the best choice for mapping structures.

Even if the images required are available in Google Earth, image analysis requires the use of GIS or remote sensing software and access to the satellite images in their original format (see Section 4.5). Accessing the data usually requires them to be purchased. Some important catalogues are:

- **IKONOS and GeoEye-1** – GeoFuse (http://geofuse.geoeye.com), which includes a toolbar extension for ArcMap and Google Earth integration tools.
- **Rapideye** – EyeFind (www.rapideye.com/products/eyefind.htm).
- **QuickBird and WorldView** – ImageFinder (https://browse.digitalglobe.com).
- **SPOT** – SPOTCatalog (http://catalog.spotimage.com).
- **Landsat** – USGS Global Visualization Viewer (http://glovis.usgs.gov).

Other data catalogues for oceanographic data have been referred to in Section 3.1 and Section 3.2.

4.5 Data formats

a key challenge for many non-remote sensing or GIS specialists is the bewildering range of data formats and projections in which remote sensing and oceanographic data are provided. Even the most common data formats can be confusing to those who are not programmers or remote sensing and GIS specialists. Although some effort and time is required to learn how to use available data and tools, there is substantial user guidance available. Table A3.11 provides a summary of the common data formats for remote sensing and oceanographic data and references to some of the tools for viewing and converting the data.

TABLE A3.11
Summary of common remote sensing formats for operational oceanography data

Name	Description	Tools and conversion
netCDF	Network Common Data Form (netCDF) is a common, machine-independent format for representing scientific data.	ArcGIS and MGET Toolbox can be used to download and import netCDF files to ESRI GRID format. Technical information on netCDF: www.unidata.ucar.edu/software/netcdf
HDF	Hierarchical Data Format (HDF) is a common, machine-independent, self-describing format for representing scientific data. Many open source and commercial tools understand HDF.	ArcGIS and MGET Toolbox can be used to download and import netCDF files to ESRI GRID format. ArcGIS has built-in capabilities to import HDF Technical information on HDF: www.hdfgroup.org
GeoTiff	GeoTIFF is a public domain metadata standard that allows georeferencing information to be embedded within a TIFF file, such as projections, coordinate systems, ellipsoids, datums. It provides a TIFF-based interchange format for georeferenced raster imagery.	Most GIS and remote sensing software packages support GeoTIFF. Technical information on GeoTIFF: http://trac.osgeo.org/geotiff

It is also important to review the "metadata" (information about the data product) to ensure that the parameters provided by the product, format and level are understood. Metadata is often summarized in a data specification document or a text file.

4.6 Data costs

The cost of remote sensing data varies considerably, i.e. considering that some data are provided freely by international or national space and oceanographic agencies and other data are commercial products whereby a company is trying to run a profitable business based on data sales. Google Earth contains a valuable source of high spatial resolution data that can be browsed freely.

In almost all cases, the end users must make some compromises on the data they would like to use and what is practically and economically possible. For example, it may be desirable to have up-to-date, 1 m spatial resolution optical data for the entire coastal zone for a project area, but this may be prohibitive in terms of the cost and the data volumes may be hard to manage. Costs of imagery are not the same in different regions. For example, countries with satellite receiving stations often have lower government pricing for imagery. Space agencies may reduce pricing for their imagery for developing countries, e.g. ESA in Africa or the Japan Aerospace Exploration Agency for parts of southeast Asia.

It is best first to investigate what national government departments or agencies have available. The range of potential applications and size of areas of interest is an important factor. It is important to remember that there are costs associated with fieldwork, image processing and analysis, accuracy assessment and cartography that must also be considered. Labour costs will often greatly exceed the data costs, depending on the labour costs in the region. A scoping study is an essential step to determine if a proposed activity or application is economically feasible and sustainable.

As an indicative guide, the typical cost of data for some common aquaculture applications is provided in Table A3.12. The table shows the total cost for data is the cost before image processing; however, data products can be purchased at these prices (with the exception of ALOS PALSAR) with certain image processing already completed. The number of images is also estimated, although this depends on the shape of the area of interest, and many products are now available at prices based on the area of data required rather than images or "scenes". It is important to know that prices change and the market for satellite data is becoming more competitive.

TABLE A3.12

Indicative costs of satellite image data for typical aquaculture application

Mapping aquaculture structures			
Size of the area	**500 km^2**		
Sensor type	**Imaging radar**		**High resolution optical**
Data type/mode	**ALOS PALSAR, fine beam**	**TerraSAR-X, StripMap**	**IKONOS or QuickBird**
Spatial resolution (m)	10	3	1
Estimated number of images	1	1	3–4
Example mapping scale	1:30 000	1:15 000	1:5 000
Cost (US$/km^2)	0.5–1	5–8	10–20
Total cost for data (US$)	**500–1 000**	**5 000–8 000**	**10 000–20 000**

4.7 Software and tools

Remote sensing data cannot be considered in isolation from the systems that are required to acquire, manage, analyse and integrate data, and also to present results as the information products. Remote sensing is often viewed as a source of data for integration into a GIS, but there are increasing examples of data being incorporated into Web-based or desktop applications that are not GIS, such as Google Earth (http://earth.google.com) and CoastWatch (http://coastwatch.noaa.gov). There are a large number of software products and add-on tools that alone, or in combination, provide data management and analysis tools for available operational oceanography data.

It is important to explore different free and/or open source GIS and remote sensing software to discover if software can support the analysis that is required. An index of

some open source projects is available at http://opensourcegis.org. Some good and free remote sensing options are the following:
BEAM (www.brockmann-consult.de/cms/web/beam) - toolbox and development platform for viewing, analysing and processing of medium-resolution remote sensing data from MODIS, MERIS, AVHRR, AVNIR, PRISM and CHRIS/Proba. Various data and algorithms are supported by dedicated extension plug-ins. BEAM has a good user interface and operates under the Microsoft Windows environment.
Google Earth (http://earth.google.com) – Google Earth allows users to view images obtained from satellite imagery and aerial photography on top of a 3-dimensional model of the Earth. Google Earth provides access to a range of data in the Layers section of the sidebar, including access to the Earth Gallery that contains many different types of ocean data provided by third parties (e.g. the United States Navy provides daily SST data). Many other organizations provide access to Keyhole Markup Language (KML)[15] files to explore ocean data.

Google Earth provides an easy-to-use overview of the geography of an area using satellite imagery selected by Google – high-resolution data can be especially useful for identification and localization of aquaculture structures. The drawing tools in Google Earth provide a simple way to create and annotate geographic features such as cage locations, supporting facilities and ports. Google Earth is not a comprehensive satellite image catalogue, and Google generally focuses on providing imagery over land and coastal areas, which may not be able to include some areas of interest for offshore mariculture. More images are usually available than those available in Google Earth/Maps, and it is, therefore, important to obtain a complete list of remote sensing data from one or more online data catalogues in order to choose remote sensing data for a monitoring project. An interesting example of the use of Google Earth was an assessment of the spatial distribution of fish cages and pens among 16 countries in the Mediterranean (Trujillo, Piroddi and Jacquet, 2012), which showed that 80 percent of the installations were within 1 km of the coast and that the maximum distance offshore was about 7 km.
Google Maps is a web-mapping service application and technology provided by Google, free (for non-commercial use), that powers many map-based services, including the Google Maps Web site. The simplest online mapping service provided by Google is referred to as Google My Maps.

No programming knowledge is required to make a map; simple point and click editing can be easily used to create an interactive online map. My Maps can be created collaboratively and can easily be embedded in any Web site. The only technical requirement needed for the use of My Maps is a Gmail or Google account (which are both free). For more advanced mapping applications, Google application programming interface (API) can be employed. While the maps created with the Google API can be much more advanced than those created with My Maps, a significant amount of additional coding skills are required.
Tutorials and Webinars on Google Earth and Maps:

- Ecosystem-Based Management Tools (www.ebmtools.org/search/node/Google);
- Geospatial Technologies Training Center. Making Maps the Google Way (http://extension.unh.edu/GISGPS/GISGPSTM.cfm); and
- Google Earth Web site (http://earth.google.com/outreach/tutorials.html).

ILWIS (www.ilwis.org) – free GIS software with a comprehensive set of image processing tools and capabilities for image georeferencing, transformation and making image mosaics.

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[15] Keyhole Markup Language (KML) is an annotation for expressing geographic annotation and visualization within Internet-based, two-dimensional maps and three-dimensional Earth browsers. KML was developed for use with Google Earth, which was originally named Keyhole Earth Viewer. It was created by Keyhole, Inc., which was acquired by Google in 2004.

Marine Geospatial Ecology Tools (MGET; http://code.env.duke.edu/projects/mget) – provides a "geoprocessing toolbox" of more than 180 tools for coastal and marine researchers and GIS analysts who work with spatial ecological and oceanographic data. The tool is designed for ArcGIS (ESRI – Environmental Systems Research Institute), the leading commercial GIS software, which obviously limits its availability to ESRI GIS software users.
Next ESA SAR Toolbox (NEST; http://earth.esa.int/nest) - NEST is an ESA toolbox with an integrated viewer for reading, post-processing and analysing ESA and third-party synthetic aperture radar (SAR) data. NEST allows users to further develop the software package by means of a Java API. NEST is developed by Array Systems Computing, Inc., under contract with ESA.
Quantum GIS (www.qgis.org) – Quantum GIS is a user-friendly open source GIS and is an official project of the Open Source Geospatial Foundation. It runs on Linux, Unix, Mac OSX, Windows and Android, and supports numerous vector, raster and database formats and functionalities. It also provides access to standard Internet data services, such as the Web Map Service (WMS), Web Feature Service (WFS), and Web Coverage Service (WCS), and the capability to open Google Earth KML files.
Radar Tools (http://radartools.berlios.de) – tool for processing radar data. Advanced algorithms in SAR polarimetry (PolSAR), interferometry (InSAR) and polarimetric interferometry (PolInSAR) included.
SPRING (www.dpi.inpe.br/spring/english) – SPRING is a free state-of-the-art GIS and remote sensing image processing system, which integrates raster and vector data representations in a single environment. SPRING is a product of the National Institute for Space Research in the Federative Republic of Brazil.
User-friendly Desktop Internet GIS (uDIG;(http://udig.refractions.net/) – uDig is an open source Java desktop GIS application that supports data access, editing and viewing. uDig provides access to standard Internet data services, such as WMS, WFS, WCS, and the capability to open Google Earth KML files.
World Wind (http://worldwind.arc.nasa.gov/java) – a good alternative to Google Earth is NASA World Wind, which is a similar type of software but uses NASA imagery and allows the user to choose specifically the type of imagery to view.

A few examples of some of the main proprietary remote sensing software are listed below:

- ERDAS IMAGINE (http://geospatial.intergraph.com/Homepage.aspx) – one of the leading image analysis software packages developed by Intergraph.
- ENVI (www.ittvis.com/language/en-us/productsservices/envi.aspx) – this is also a leading proprietary supplier of image analysis software.
- ArcGIS (www.esri.com) – ArcGIS is the leading commercial GIS software package, offering an integrated collection of GIS software products. There are numerous extensions to the software, some of which are free such as MGET (described above).
- IDRISI (www.clarklabs.org) – as a commercial GIS and remote sensing software, it is relatively cheap, user friendly and very powerful.
- Manifold (www.manifold.net) – Manifold is a cost-effective GIS software package that can be used to integrate a variety of oceanographic data in available formats.

5. Demonstration products and case studies

Demonstration products and case studies in the subsections below are relevant to the safe environment and healthy environment parameters that can be derived from remote sensing data. The overall aim is to introduce the types of products that can support offshore mariculture and the processing steps and software tools used.

5.1 Wave heights and winds

Objective

The objective is to demonstrate how the data sets of wave heights and winds can be analysed to provide information on suitable aquaculture areas using threshold ranges for individual typical aquaculture structures.

Data

The data sets used to create demonstration products are described in Table A3.13 and Table A3.14. For the purpose of developing the demonstration map products, additional data included the EEZ Maritime Boundaries Geodatabase (Version 5, 1 October 2009) from www.vliz.be/vmdcdata/marbound, and coastline data and national boundaries from ESRI Map and Data 2008 (www.esri.com).

TABLE A3.13

SWH suitability demonstration data

Data set	AVISO significant wave height; downloaded using MGET (see processing section)
Format	NetCDF
Download size	~1 MB
Spatial extent	Global
Spatial resolution	1 degree (~90 km)
Timeliness/time period	Available "daily" data from June 2008 (total of four products)

TABLE A3.14

Wind suitability demonstration data

Data set	AVISO surface wind; downloaded using MGET (see processing section)
Format	NetCDF
Download size	~1 MB
Spatial extent	Global
Spatial resolution	1 degree (~90 km)
Timeliness/time period	Available "daily" data from June 2008 (total of four products)

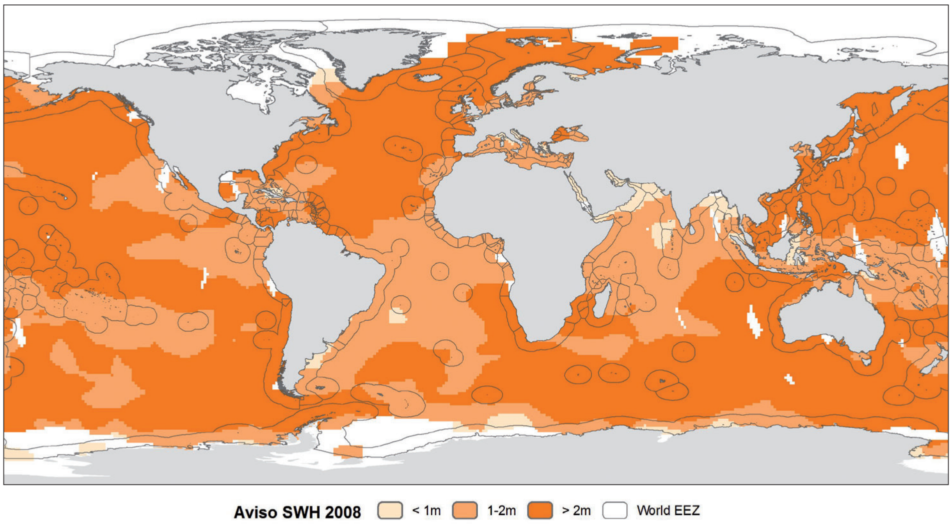
Processing

The image processing steps to create the demonstration suitability products are similar to the ones described in more detail later in section 5.2. The software used for processing and analysis of SWH and wind data was ESRI ArcGIS 9.3. The AVISO data were downloaded and converted from Hierarchical Data Format (HDF) to ESRI GRID using MGET. AVISO data are daily, and so a time range was specified as part of the MGET download process, which selected SWH and wind data for the month of June 2008. The daily data available in June 2008 were only for four days (4, 11, 18 and 25 June). Based on standard ArcGIS functions and the Spatial Analyst extension, the mean value was calculated. For the purposes of demonstrating the contents of the data, the SWH were arbitrarily classified into three simple classes: < 1 m; 1–2 m; and > 2 m. Likewise, global sea surface winds were also classified into three simple classes: < 2 m/s; 2–5 m/s; and > 5 m/s.

Results

Two demonstration products are shown in Figure A3.5 and Figure A3.6. Figure A3.5 shows the global SWH for June 2008 according to three simple classes (< 1 m; 1–2 m; and > 2 m). The classes in the map indicate areas where waves may be problematic for offshore mariculture, e.g. the coasts of the Republic of Chile, the Republic of Namibia and the Republic of South Africa, and the Kingdom of Norway. However, it must be stressed that the spatial resolution of the data is coarse (1 degree or ~90 km), and, in this example, the time period of the data is not a long-term or seasonal average. The strength of the data is that it provides a chance to explore and "screen" areas before undertaking more detailed studies.

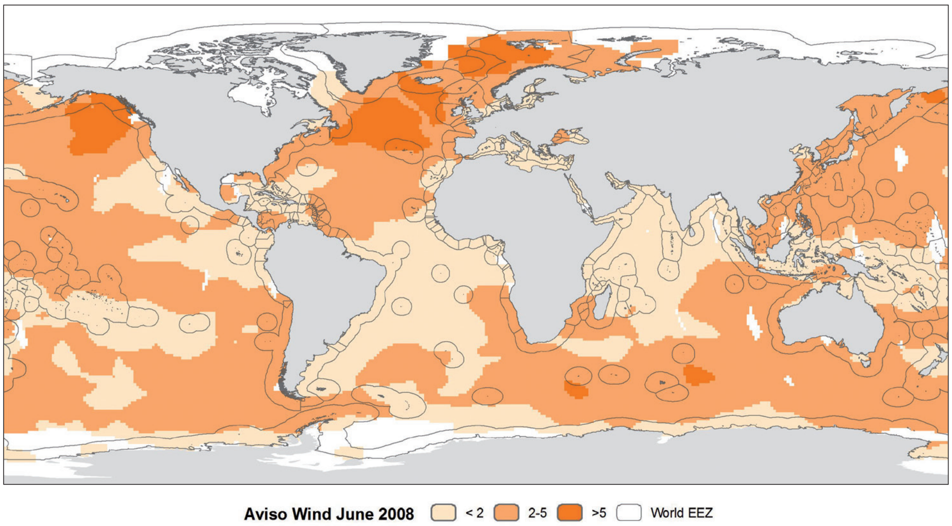
FIGURE A3.5
Global average significant wave height (metres) in June 2008



Source: AVISO (2010).

Figure A3.6 shows the global sea surface winds for June 2008 according to three simple classes (< 2 m/s; 2–5 m/s; and > 5 m/s). The pattern is similar to the SWH data, as would be expected, and again is indicative of areas that may be too exposed for offshore mariculture. Depending on the thresholds selected, more detailed patterns in SWH and surface winds may be identified, within the constraints of the resolution of the data. While some offshore fully exposed areas in Figures A3.5 and A3.6 could be considered as suitable based on significant wave height and sea surface winds, offshore mariculture development is most likely to take place relatively close to coasts within the boundaries of the EEZs.

FIGURE A3.6
Global average sea surface winds (metres sec-1) in June 2008



Source: AVISO (2010).

5.2 Sea surface temperature and productivity

Objective

The objective is to demonstrate how available SST and chlorophyll-*a* concentration data sets can support a suitability assessment for individual species and integrated multitrophic aquaculture. The suitability assessment is based on aquaculture species using threshold ranges.

Data

The data sets used to create demonstration products are described in Table A3.15 and Table A3.16. For the purpose of developing the demonstration map products, additional data included the EEZ Maritime Boundaries Geodatabase (Version 5, 1 October 2009) from www.vliz.be/vmdcdata/marbound, and coastline data and national boundaries from ESRI Map and Data 2008 (www.esri.com).

TABLE A3.15
Sea surface temperature suitability demonstration data

Data set	**Aqua MODIS Seasonal Climatology Sea Surface Temperature (http://oceancolor.gsfc.nasa.gov/cgi/l3)**
Format	PNG image, HDF Standard Mapped Image, HDF Binned
Spatial extent	Global
Download size	25–30 MB (compressed file)
Spatial resolution	4 km and 9 km
Timeliness/time period	Seasonal climatology data averaged for the period 2002–2009
Attributes	SST value in degree °C

TABLE A3.16
Chlorophyll-*a* concentration suitability demonstration data

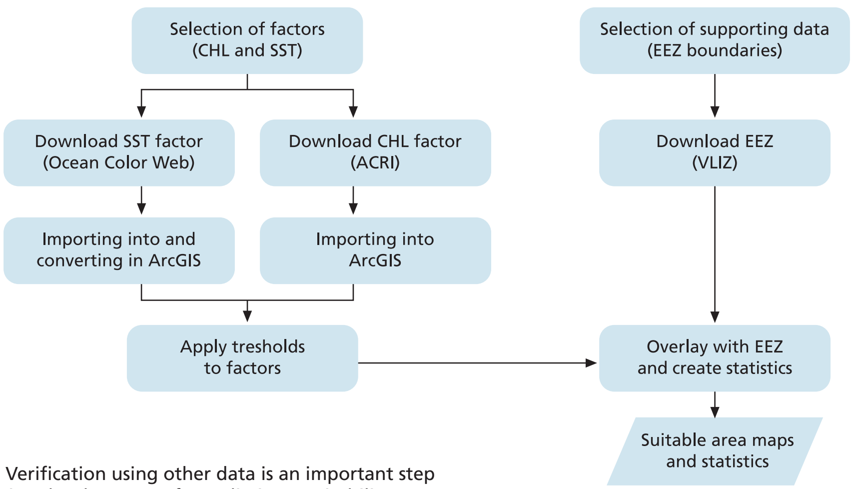
Data set	ACRI-ST InfoceanDesk environment monitoring service (http://hermes.acri.fr)
Format	GeoTIFF (geographic)
Download size	50–100 MB (compressed file)
Spatial extent	Global and custom region
Spatial resolution	4.6 km
Timeliness/time period	Seasonal climatology data averaged for the period 1998–2009
Attributes	Chlorophyll-*a* concentration in mg/m^3

Processing

The image processing steps to create the demonstration suitability products are shown in Figure A3.7. The software used for the processing and analysis was ESRI ArcGIS 9.3.

The first step was to select the factors required for the analysis – chlorophyll (CHL) and SST. The chlorophyll-*a* concentration data were provided by ACRI and in GeoTIFF format so that they could be opened directly in ArcGIS. The SST data from OceanColorWeb were converted from HDF to ESRI GRID using MGET toolbox. Based on standard ArcGIS functions and the Spatial Analyst extension, thresholds described in Table A3.17 were applied to the data. For more information on the conditions and issues for cultured species, refer to the FAO cultured species online database (www.fao.org/fishery/culturedspecies/search/en). Finally, the EEZ boundaries data sets were downloaded and overlain with the analysed CHL and SST data, using ArcGIS, to produce the suitable area maps and data.

FIGURE A3.7
Image processing steps to create offshore mariculture suitability map products



Note: Verification using other data is an important step following development of a preliminary suitability map

TABLE A3.17
Example thresholds applied to sea surface temperature and chlorophyll-*a* concentration data

Species	Suitability criteria	Value
Cobia (*Rachycentron canadum*)	SST long-term maximum and minimum	26–32 °C
Atlantic salmon (*Salmo salar*)	SST long-term maximum and minimum	8–16 °C
Blue mussel (*Mytilus edulis*)	SST long-term maximum and minimum	5–20 °C
	Chlorophyll-*a* concentration monthly averages	> 1 mg/m^3

Results

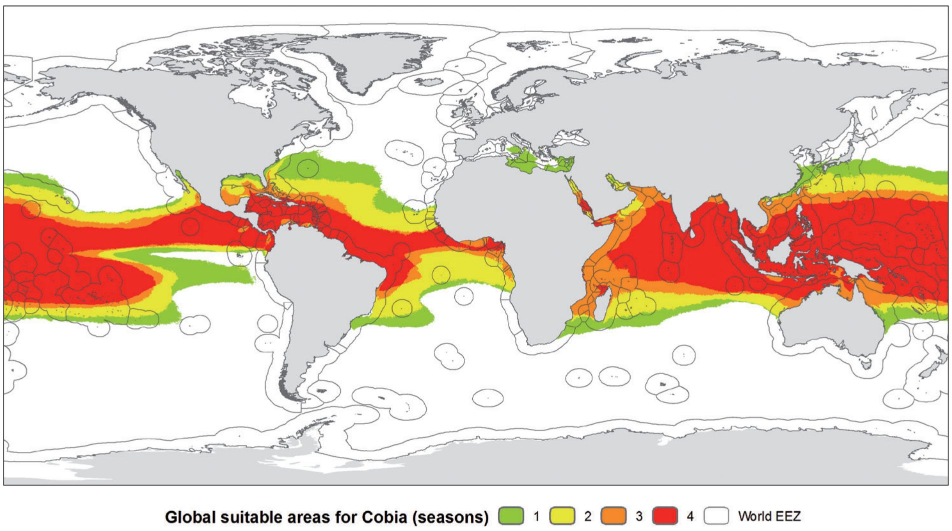
A series of demonstration products are shown in Figures A3.8 to A3.10.

Figure A3.8 shows the global areas suitable for cobia (*Rachycentron canadum*); the different SST range for this species providing a range focuses on tropical waters. According to FAO, the largest producer of this species is the People's Republic of China (www.fao.org/fishery/culturedspecies/Rachycentron_canadum/en); however, the temperature levels are considered more suitable in tropical waters.

Figure A3.9 shows the global areas suitable for Atlantic salmon (*Salmo salar*), and follows the distribution of the global Atlantic salmon aquaculture, with suitable areas being dominated by the Kingdom of Norway, the Republic of Chile, Scotland and Canada. While the offshore fully exposed areas in this figure and in Figures A3.8 and A3.9 are suitable based on SST, it is not likely that they will be developed for mariculture in the near future for economic, technical and jurisdictional reasons. Offshore mariculture development is most likely to take place relatively close to coasts within the boundaries of the EEZs shown in these and other figures. The classes in the map reveal the number of seasons where the temperature thresholds were met - the optimum being all four seasons.

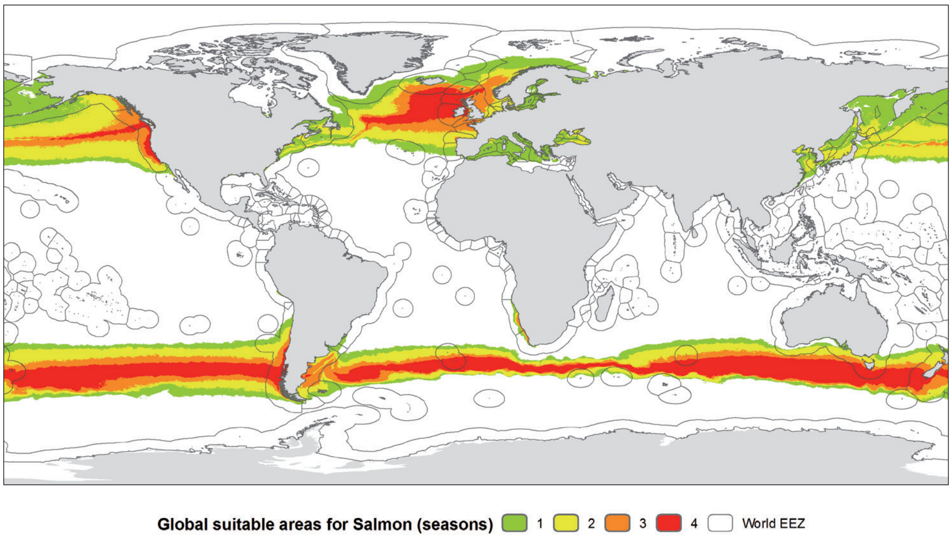
Figure A3.10 shows the global areas suitable for blue mussel (*Mytilus edulis*), which confirms some of the known cultivation areas, e.g. the Republic of Chile where a close relative of the blue mussel, *Mytilus chilensis*, is cultivated. The global analysis also indicates that the coast of the Republic of Namibia and the western coast of the Republic of South Africa are suitable, based only on SST and chlorophyll-*a* concentration data.

FIGURE A3.8
Global area suitable for cobia (*Rachycentron canadum*) based on sea surface temperature (26–32 °C)



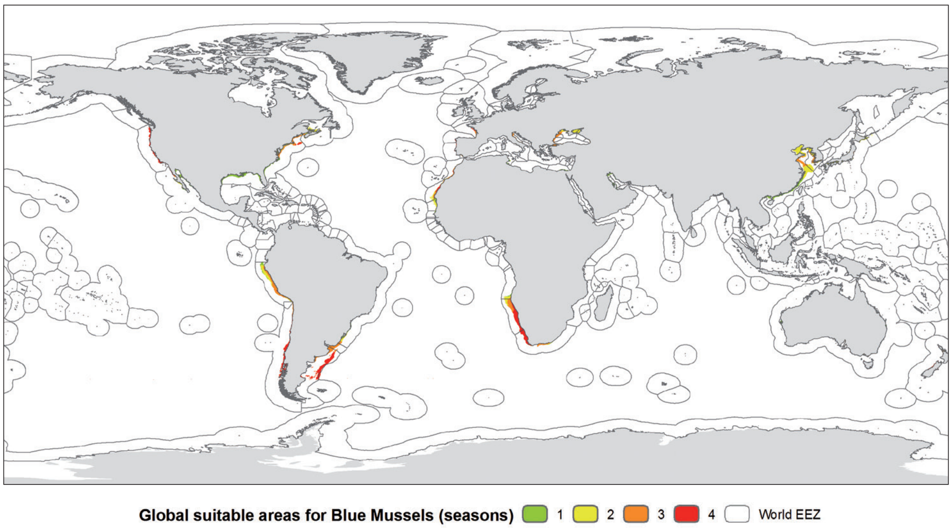
Source: Aqua MODIS Seasonal Climatology Sea Surface Temperature (http://oceancolor.gsfc.nasa.gov/cgi/l3)

FIGURE A3.9
Global area suitable for Atlantic salmon (*Salmo salar*) based on SST values from 8–16 °C



Source: Aqua MODIS Seasonal Climatology Sea Surface Temperature (http://oceancolor.gsfc.nasa.gov/cgi/l3)

FIGURE A3.10
Global area suitable for blue mussel (*Mytilus edulis*) based on sea surface temperature (5–20 °C) and chlorophyll-*a* concentration (>1 mg/m^3)



Sea surface temperature data source: Aqua MODIS Seasonal Climatology Sea Surface Temperature (http://oceancolor.gsfc.nasa.gov/cgi/l3)

Chlorophyll-a concentration data source: ACRI-ST INFOCEAN-DESK environment monitoring service (www.myocean.eu.org)

Note: As shown in Figure A3.10, the combination of sea surface temperature and Chlorophyll requirements restricts the distribution of suitable areas for blue mussel. The EEZ boundaries were not used as a mask.

A GIS is more than simply a tool for making maps, as it can also be used to produce quantified data on suitable areas within an EEZ. For example, Table A3.18 reports the EEZ area of several countries suitable for cultivating Atlantic salmon (*Salmo salar*) in 1, 2, 3 or 4 seasons according to the SST criteria used to produce Figure A3.8.

TABLE A3.18

Number of seasons the EEZ for selected countries is suitable for Atlantic salmon (*Salmo salar*) according to sea surface temperature

	Suitable area km^2 (seasons)			
Country	**1**	**2**	**3**	**4**
Canada	2 206 800	1 098 100	825 300	207 600
Chile	941 200	1 038 200	665 200	761 300
Namibia	135 900	53 200	63 500	347
Norway	3 933 800	1 559 600	1 285 300	8 900

5.3 Monitoring algal bloom development (Republic of Chile)

Original publication reference: Stockwell, A., Boivin,T., Puga, C., Suwala, J., Johnston, E., Garnesson, P. & Mangin, A. 2006. Environmental information system for harmful algal bloom monitoring in Chile, using earth observation, hydrodynamic model and in situ monitoring data. (available at www.esa.int/esaEO/SEMUS5AATME_economy_0.html).

Spatial tools: Ocean colour satellite imagery, hydrodynamic model, Web development

Main issues addressed: Harmful algal blooms and aquaculture

Duration of study: 1 year (January 2005 to February 2006)

Personnel involved: Thomas Boivin, Alan Stockwell, Cristian Puga, Jason Suwala, Erin Johnston, Antoine Mangin, Philippe Garnesson and Loredana Apolloni

Target audience: Marine aquaculture industry

Introduction and objectives: Hatfield Consultants (Hatfield), in collaboration with ACRI-ST and Apolloni Virtual Studios (AVS), collaborated on a project called "Integrating Earth Observation into Aquaculture Facilities Monitoring in Southern Chile", also referred to as the "Chile Aquaculture Project" (CAP). The CAP project was funded by ESA and conducted with Mainstream Chile, part of the Norwegian holding company CERMAQ, a world leader in salmon production.

The objective was to demonstrate integrated application of remote sensing data and modelling to provide advanced warning of potentially harmful algal blooms (HABs) so that their impacts can be minimized by the aquaculture industry. The monitoring of the conditions that indicate a high HAB risk can provide sufficient time for mitigation measures to be taken by farmers to help reduce potential losses. Long-term data can help improve the site selection process for new facilities.

Data: Several information sources were used to develop a prototype of an HAB warning system:

- Remote sensing products were provided by ACRI-ST. Chlorophyll-*a* concentration and Secchi depth transparency maps were generated on a daily basis from merged MERIS and MODIS data. Daily SST data were acquired from MODIS with in situ data from buoys.
- In situ environmental data were provided by Mainstream Chile.
- Oceanographic, meteorological and land GIS data were collected by Hatfield.

Methods: Using these inputs, an oceanographic currents and tidal model was developed, which in combination with transparency and chlorophyll-*a* products was the basis for development of a HAB risk/warning map.16 The combination of ocean colour data from different sensors and daily SST meant that product delivery was possible on a daily basis, dependent on cloud cover.

Results: The image processing system and modelling were integrated to produce automatic products of chlorophyll-*a*, SST and Secchi depth. The products were integrated with a GIS to build easy-to-interpret maps, which, along with tabular data, were also displayed via a Web portal that was updated each day. The end user could choose the level of detail required by selecting overview maps of the aquaculture production area (e.g. Chiloe Island area) or by selecting specific salmon farm sites to analyse available data. An example of the Web portal page is shown in Figure A3.11, which shows an overview map with a 15-day average of chlorophyll-*a* concentration.

Validation using in situ and other data enabled accuracies to be estimated as follows:

- chlorophyll-*a*: within 15 percent;
- SST: within 0.5 °C;
- Secchi depth: ± 2 m (after algorithm recalibration);
- tide elevation from model: 10 cm at the Puerto Montt control point (astronomical tides); and
- surface current: estimated to be within 1 m/s (but with few means of validation).

Discussion and recommendations: According to the needs of users and the state of the technology, the main focus for HAB warning is on the delivery of chlorophyll-*a* data and on Secchi depths (SST is obviously of importance as well as to support modelling). Based on the CAP experience, there was a need for improvements in the accuracy and quantification of the error for the products. Secchi depths should be within an error of 2 metres (± 1 m).

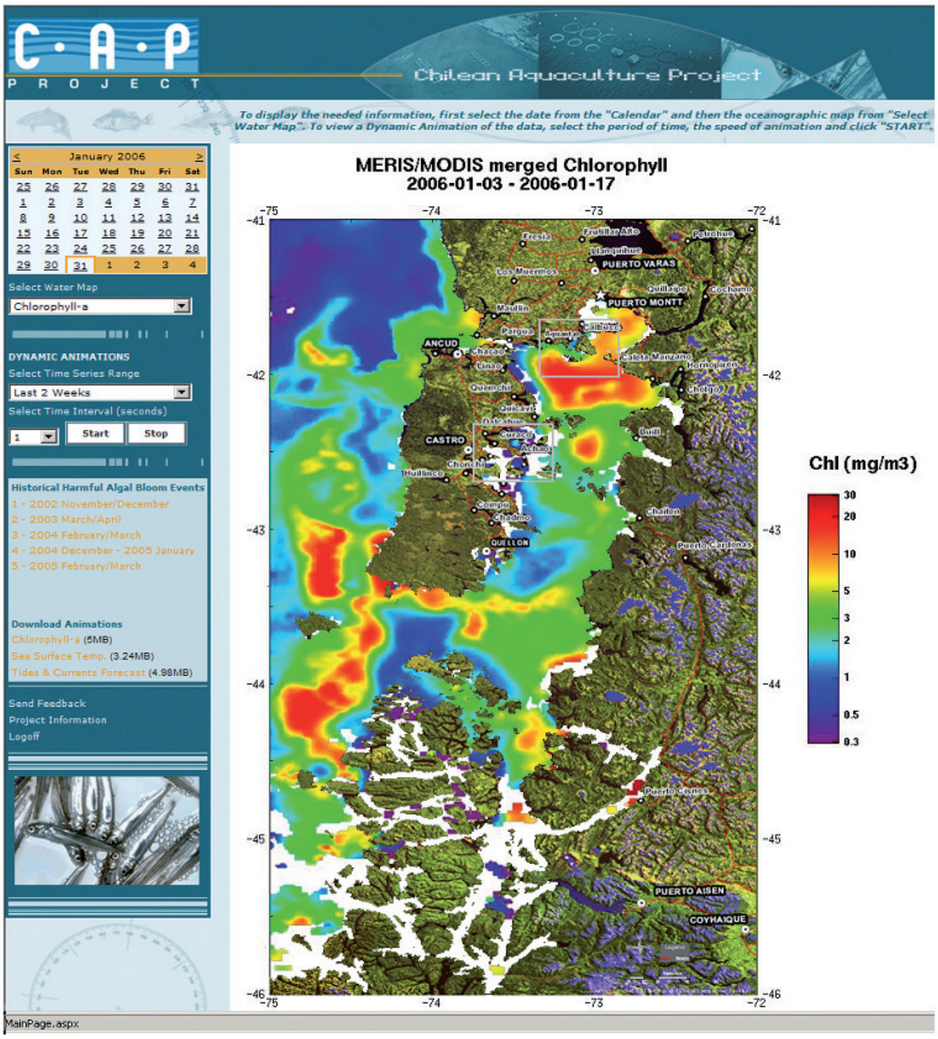
In addition to HAB warnings, another recommendation was the exploitation of available ocean colour remote sensing data to derive maps of statistics of chlorophyll-*a* persistence, variability and other statistical parameters at high resolution (e.g. 1 km spatial resolution). This type of climatology information is extremely valuable for site selection for aquaculture production areas. Also, to improve the understanding of the evolution of the environmental parameters, automatic procedures could strongly benefit the system; for example, chlorophyll-*a* front extraction by local gradient computations and quantification of differences between one daily scene and the previous scene(s).

Finally, for users there is a real need for derivation of a synthetic “HAB index” that includes all relevant environmental components. This synthetic HAB index could be expressed in the form of a very simple graphic (ideally three colours from green to red, meaning non-risk to high risk).

The CAP project provided important information on HAB occurrences in the key aquaculture regions of southern Republic of Chile, which proved to be extremely valuable to the industry and local government. Long-term monitoring of HAB information is important to help protect the aquaculture industry from possible losses in production, which can be significant in the event of a major HAB event.

[16] HABs and normal CHL are not separated or detected directly. The inputs are combined to determine HAB risk.

FIGURE A3.11
Chile Aquaculture Project Web portal – main page



Source: Hatfield Consultants (2009).

5.4 Coastal fisheries and aquaculture structure mapping in the Lingayen Gulf, the Republic of the Philippines

Original publication reference: Travaglia, C., Profeti, G., Aguilar-Manjarrez, J. & Lopez, N.A. 2004. Mapping coastal aquaculture and fisheries structures by satellite imaging radar: case study of the Lingayen Gulf, the Philippines. FAO Fisheries Technical Paper No. 459. Rome, FAO. 2004. 45 pp. (also available at www.fao.org/docrep/007/y5319e/y5319e00.htm).

Spatial tools: Remote sensing

Main issues addressed: Inventory and monitoring of aquaculture and the environment

Duration of study: Six months; the study began in 2003 and ended in 2004

Personnel involved: (i) Remote sensing specialist with a working knowledge of remote sensing applications in fisheries and aquaculture (FAO Remote Sensing Officer) assisted with the design of the study and analyses and managed the project; full time. (ii) Fisheries and aquaculture specialist with a working knowledge of GIS and remote sensing applications (FAO Aquaculture Officer) assisted with the design of the study; part time for the duration. (iii) Digital image processing specialist (consultant and professor) provided modelling, image processing and analyses; full time. (iv) Philippine aquaculturist, who wrote the description of the structures (fish pens, cages and traps) and played a key role in ground verification; part time for the duration. (v) Field verification personnel from the Bureau of Fisheries and Aquatic Resources of the Philippines (four staff); full time for short duration. (vi) Advisers at large (four advisers), who provided data and advice from time to time.

Target audience: The study is aimed at the general fisheries and aquaculture public, governmental administrators and planners, and remote sensing and GIS specialists.

Objective: The objective of this FAO-led study was to test, under operational conditions, a methodology for inventory and monitoring of shrimp farms using radar satellite imagery. The study focused on various types of structures (onshore fish ponds, fish pens in the tidal zone, and offshore cages and traps in the Lingayen Gulf, the Philippines) and aimed to compare the suitability of different types of imagery.

Data: Radar data are known to offer unique capabilities for mapping shrimp farms, not only for their inherent all-weather capabilities (important in tropical and subtropical areas), but also for the way radar interacts with pond dykes (Travaglia, Kapetsky and Profeti, 1999). Pond dykes are distinguishable from surrounding water surfaces and from the much lower dykes surrounding rice paddies and other flooded areas. The study area was covered by two ERS-2 SAR images acquired in descending and ascending orbits in December 2002 with a spatial resolution of 25 m – see Dean and Populus (2013) for description of satellite orbits. Orbit direction is relevant because it influences the characteristics of the SAR images, and aquaculture features are enhanced in a complementary way. A RADARSAT-1 Fine Mode SAR image was acquired in February 2001 with a ground resolution of 9 m, which covers a smaller area than the ERS images but covered the majority of the area where the aquaculture and fisheries structures are located.

Methods: The images were geometrically corrected. A fish pond dyke reflects back a large amount of the incident radar energy, but this varies with the angle between the object and the direction of the incident beam. Hence, if a dyke is parallel to the radar beam it may not be detected, which is why ascending and descending orbits were acquired. The other aquaculture and fisheries structures influence the radar signal in a similar way. The vertical sides of fish cages, pens and traps, emerging from the water surface, create a corner reflector effect that allows them to be identified.

Classification (feature extraction) was conducted using visual interpretation, as described in Dean and Populus (2013). This means that a skilled image analyst manually identified and digitized the boundaries of the aquaculture structures. The validation data for an accuracy assessment was collected during field surveys by a team of the Bureau of Fisheries and Aquatic Resources of the Philippines.

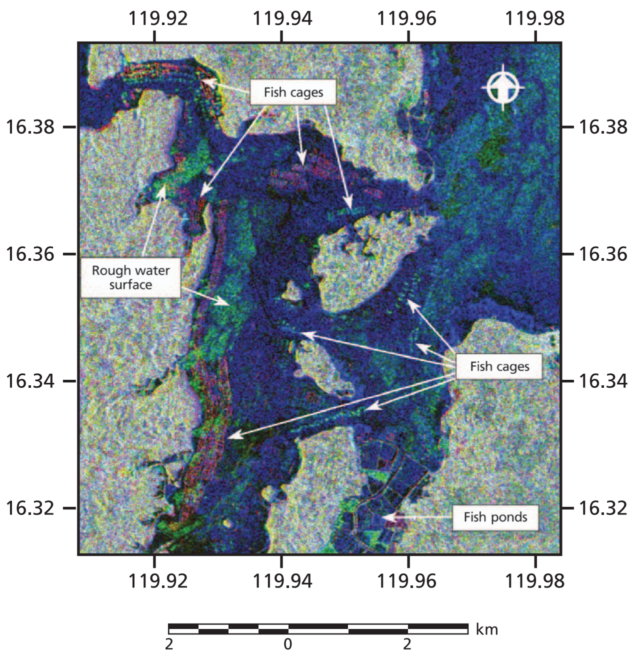
Results: The presence of the elevated surrounding dykes ensured straightforward visual interpretation. The area having fish ponds in 2002 was compared with the area mapped in 1977 topographic maps; the area had increased by 60 percent, but some of the ponds mapped in 1977 had been converted to other uses.

Fish cages were detected in all images; however, environmental conditions, such as windy conditions causing rough sea surfaces, at the time of scene acquisition negatively affect their detectability. Fish cages may be of several shapes (square, rectangular, circular) and made of various materials. Those mainly made of metal have a brighter appearance on SAR images, a common detection characteristic in radar technology. Fish traps that appeared on the sea surface were separated into two categories: offshore traps and traps inside major rivers. The area occupied by fish traps was calculated to estimate their extension. In many cases, only the central structure of the traps is visible in the images. However, because of their small size, the uncertainty on identification of traps was higher than that of the other structures.

An example of the RADARSAT-1 imagery and the images ability to map aquaculture structures is provided in Figure A3.12.

The accuracy of the visual interpretation procedure was close to 100 percent for all structures except for fish cages and traps, as they may have been moved in the time interval between the image acquisition and the field verification. The clear appearance of fish cages in the SAR imagery permitted a 90 percent estimated mapping accuracy. Mapping accuracy for fish traps was estimated at 70 percent (for fish traps of the type that had potential to be detected by remote sensing).

FIGURE A3.12
Interpreted RADARSAT-1 SAR image and the resulting map of the aquaculture and fisheries structures



Source: Travaglia *et al.* (2004).

Discussion and recommendations: RADARSAT fine mode imagery provided the best "detectability" for all aquaculture and fisheries structures considered in this study and, therefore, allowed them to be inventoried and monitored with greater accuracy. ERS imagery enabled successful mapping of fish ponds and fish cages, but failed to map fish pens and fish traps. For mapping fish ponds and fish cages, using images from ascending and descending orbits acquired within a limited time interval is recommended.

Following this study, the same authors verified the possibility of integrating optical data into monitoring coastal fisheries and aquaculture structures (G. Profeti, personal communication, 2012). They examined high-resolution optical data (e.g. IKONOS, GeoEye, QuickBird, WorldView and SPOT HRV) acquired over the study area in the same time period in which radar data were acquired, but no suitable archive data were found, even if the period was extended to two years. The lack of available data may be due to persistent cloud cover, or because commercial operators may not acquire data in many areas where commercial sales will not be made. The availability of optical and radar data cannot be assumed, and in many cases acquisitions must be carefully planned and ordered.

Since the study was completed, there have been significant developments in imaging radar as described in Dean and Populus (2013), especially the new high-resolution sensors, and there are cost-effective options for imagery. The potential application of radar includes monitoring of bluefin tuna cages in the Mediterranean Sea fishing grounds. A recent study by Pereza et al. (2011) demonstrated that floating cages towed by vessels to transport live tuna towards inshore farms have a unique signature in the radar images based on their distinctive texture pattern and position with respect to the towing vessel.

5.5 Use of remote sensing for mapping seagrass

Original publication reference: Pasqualini, V., Pergent-Martinia, C., Pergenta, G., Agreila, M., Skoufasb, G., Sourbesc, L. & Tsirikad, A. 2005. Use of SPOT 5 for mapping seagrasses: an application to Posidonia oceanica. Remote Sensing of Environment, Vol. 94: 39-45.

Spatial tools: SPOT-5 multispectral imagery, GIS

Main issues addressed: Environmental impacts of aquaculture; management of aquaculture together with fisheries

Duration of study: Not reported

Personnel involved: Not described

Target audience: Coastal management community

Introduction and objectives: *Posidonia oceanic*a is the dominant seagrass in the Mediterranean Sea (Marba *et al.*, 1996). *P. oceanica* plays an important role in many coastal processes, contributing to sediment deposition and stabilization and to attenuating currents and wave energy (Fornes *et al.*, 2006). Seagrass meadows are also considered to be among the most productive ecosystems, supporting diverse flora and fauna and providing nursery and breeding grounds for many marine organisms (Francour, 1997; Hemminga and Duarte, 2000). *P. oceanica* is a slow-growing climax species17 that forms large stable meadows, but there is evidence of decline in many areas as a result of warming sea temperatures and pollution (Marba et al., 1996; Marba and Duarte, 2010).

Potential sites for coastal aquaculture may affect ecologically sensitive areas such as coral reefs and seagrass beds, but offshore sites may still need to consider potential impacts on sensitive areas such as *P. oceanica* meadows and apply the precautionary principle. Maps of the distribution of *P. oceanica* are required for effective management and conservation.

A wide range of methods may be used for mapping seagrasses (McKenzie, 2003), including optical satellite and aerial remote sensing and acoustic sampling. Generally, the key challenges for mapping *P. oceanica* using optical images are: (i) limited light penetration to the maximum depth of *P. oceanica* distribution (about 40 m); and (ii) spatial resolution of the sensor in relation to the potential patchy distribution of P. oceanica with substrates such as rock and sand. Aerial photographs (Pasqualini et al., 1998, 2001), Compact Airborne Spectrographic Imager (CASI) (Mumby and Edwards, 2002) and IKONOS imagery have been employed in recent studies to map seagrasses.

[17] Climax species are plant species that will remain essentially unchanged in terms of species composition for as long as a site remains undisturbed.

Pasqualini *et al*. (2005) investigated the potential of SPOT-5 optical satellite imagery for mapping *P. oceanica* in Zakynthos Marine National Park (Mediterranean Sea, the Hellenic Republic). The objective of the study was to examine the potential of different spatial resolution SPOT-5 images to map seagrass in Laganas Bay, part of the National Park. The bay is 12 km long and 6 km wide with seagrass known to range from the near surface to approximately 30 m depth. Four types of community and seabed type are found: mobile sediments (silts and sands), communities on hard substrates (including shingle), continuous beds of P. oceanica, and mosaics of beds (on a mat, rock or sand).

Data: SPOT-5 imagery has four spectral bands: green (0.50-0.59 µm); red (0.61-0.68 µm; near infrared (0.78-0.89 µm); and mid-infrared (1.58-1.75 µm). The first three bands have a spatial resolution of 10 m while the mid-infrared has a resolution of 20 m. A combination of multiple SPOT-5 images acquired at the time also provides multispectral imagery enhanced to 2.5 m spatial resolution. Because there is little penetration of longer infrared wavelengths through the water column, only the green and red visible bands were used at 10 m and 2.5 m resolution in a SPOT-5 imagery acquired on 1 September 2003.

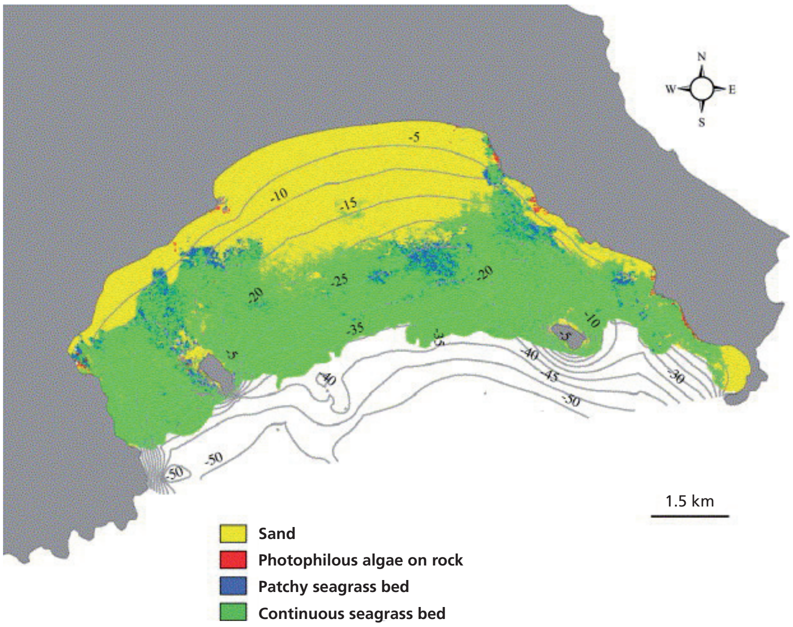
Methods: The processing of the two SPOT images was carried out using Multiscope software (Matra Systems and Information). The terrestrial part was masked in order to optimize the distinction between communities and types of seabed in the marine part. Principal component analysis was applied to the two bands in each image. A supervised classification was then applied separately to the depth layers 0–10 m and 10–20 m so as to minimize any confusion between classes due to depth. This technique was previously applied on aerial photographs (Pasqualini *et al.*, 1997), and caution is required because it can result in classification bias near the depth limit boundary.

Classification training data were 189 field observations points obtained by scuba diving or by observing the seabed from a boat. These data enabled the communities and types of seabed in Laganas Bay to be identified. The accuracy of the habitat maps was determined using the overall accuracy. Subsequently, some manual corrections were made, for example, masking beyond the maximum possible depth of P. oceanica beds.

Results: The classification results revealed the predominance of *P. oceanica* beds in the bay, from the surface down to a depth of about 30 m. The map at 10 m resolution is shown in Figure A3.13 – a large area of sand occupied the northeast of the bay down to a depth of 20 m, while the southeast and northwest were occupied by large rocky slabs, colonized by photophilous algae. These rock-dwelling photophilous algae were absent beyond the 10 m isobath. On the maps with a resolution of 2.5 m, substantial areas of patchy seagrass beds were identified over the whole of the depth range studied.

Discussion and recommendations: The overall accuracy of the habitat maps ranged from 73 to 96 percent. The 10 m image provided a better overall accuracy for each depth band. Sand was mapped least accurately. The patchy seagrass beds were mapped with a higher degree of accuracy by the SPOT 2.5 m because the improved spatial resolution revealed the patchiness of the habitat.In summary, SPOT image classification was considered a valuable method for a rapid identification of seabed types. The large image size of SPOT-5 makes it an attractive tool for the management of coastal waters; however, SPOT-5 and several other sensors lack a blue spectral band. Since the study by Pasqualini *et al.* (2005), WorldView-2 was launched in 2009 with a 1.8 m resolution visible spectrum "coastal band" (400–450 nm) that penetrates the water to greater depth. This sensor offers potential for improved and detailed mapping of *P. oceanica* beds. This type of remote sensing classification could also be useful to inventory commercial culture of seaweeds.

FIGURE A3.13
Main benthic assemblages and bottom types at Laganas Bay, Greece, based on classification of a SPOT5 image (10 m resolution)



Source: Pasqualini *et al.* (2005).

In general, satellite-based methods offer most potential in shallow waters where significant *P. oceanica* losses caused by human impact are expected to occur. The use of remote sensing, coupled with GIS, could be of immense value to supporting improved coastal management decisions and in environmental impact assessments for assessing the potential impacts of aquaculture on coastal environments on *P. oceanica* meadows.

6. Conclusions

Advances in remote sensing systems, communications technology and computer processing mean that oceanographic remote sensing data are becoming more accessible, and these products should be useful for offshore mariculture applications. Many obstacles that had once hindered the application of remote sensing are now less problematic, including affordability, information content, timeliness and delivery frequency. Several important information requirements related to a healthy environment for the growth and well-being of cultured organisms can be met through remote sensing, including temperature, primary productivity and turbidity. Information on the safety of aquaculture structures can also be provided from processed satellite radar altimetry and coastal HF radar, although the freely available wave, wind and currents products have a spatial resolution that is too coarse for most applications.

For an offshore mariculture global and regional "site suitability assessment", remote sensing data can provide important data for integration and analysis within a GIS. Suitability assessment requires integration of additional data sets, such as bathymetry, accessibility (distance to ports), and management related information such as infrastructure. "Site selection and zoning" requires higher spatial resolution imagery products, and several freely available data sets include chlorophyll-*a* concentration, turbidity and SST. Suitable data on currents, waves and winds require engaging with suppliers such as AVISO, HYCOS consortium, or any agency managing HF radar. "Monitoring" applications for offshore mariculture usually demand at least daily observations and information reports on the environmental status (e.g. currents or chlorophyll-*a* concentration), which can be a challenge because of cloud cover for optical satellite sensors. Currents are highly variable, so the hourly data that are possible from HF radar is most appealing. For ocean colour observation, such as chlorophyll-*a* concentration, no single satellite provides daily coverage, which means that information services such as the ACRI-ST InfoceanDesk environment monitoring service (www.myocean.eu.org) are based on integration of several satellites.

International and national space agencies, recognizing the user requirements for satellites at the mission design stage, are set to launch tandem or constellation missions (e.g. Sentinel-1 in 2013; RADARSAT Constellation in 2014) that will increase the observation frequency. However, despite progress with the technology, many potential users of remote sensing data lack access to training, support, and tools to acquire different data sets and use them to support their activities. Thanks to the efforts of several international organizations, such as the Census of Marine Life, there are many well-documented applications of remote sensing for marine applications as well as simple guides to download and convert remote sensing data. This review provides some simple options to acquire data and begin to process data for incorporation into further analysis using GIS of relevance to offshore mariculture.

In conclusion, aquaculture is practised worldwide in highly variable environments, but the biological systems and sustainable human exploitation are controlled to a greater or lesser extent by many variables that can be measured by remote sensing. It is likely that remote sensing will play a more important role in planning and management activities, and also monitoring. The unique capability of satellite remote sensing to provide regular, repeated observations of the entire globe or specific regions at different spatial scales will also become increasingly important in the context of global climate change and the EAA. The time series of information products that are operationally derived from remote sensing should be part of government assessments of climate change impacts and action plans for industry adaptation. Another related concern is ocean acidification as a result of oceans absorbing about 50 percent of the carbon dioxide released from the burning of fossil fuels, which results in an increase in ocean acidity. Remote sensing will be an important tool in future studies of ocean acidification, which will require development and validation of models along with in situ data.

7. Glossary

Electromagnetic radiation. Energy propagated through space or through material media in the form of an advancing interaction between electric and magnetic fields.

Orbit. (1) The path of a body or particle under the influence of a gravitational or other force. For instance, the orbit of a celestial body is its path relative to another body around which it revolves. (2) To go around the Earth or other body in an orbit.

Geosynchronous orbit. An orbit around the Earth whereby a satellite travels in a general west-to-east direction and completes the orbit in the same time as the Earth completes a revolution.

Incidence angle. In radar, the angle formed between an imaginary line normal to the surface and another connecting the antenna and the target.

Platform. The vehicle that carries a sensor, i.e. satellite, aircraft, balloon, etc.

Polarization. A property of an electromagnetic wave that describes the locus of the electric field vector as a function of time.

Remote sensing. The science, technology and art of obtaining information about objects or phenomena from a distance (i.e. without being in physical contact with them).

Resolution. Resolution is the ability of a sensor to distinguish two closely spaced objects or lines as two rather than one object or line. Alternately, it is the smallest object or narrowest line a sensor can detect.

Satellite. A vehicle put into orbit around the Earth or other body in space and used as a platform for data collection and transmission.

Sensor. A device that measures the electromagnetic energy that is emitted or reflected by features of the Earth's surface and converts it into a signal that can be recorded and displayed as either numerical data or an image.

Sun-synchronous orbit. The path of a satellite in which the orbital plane is near polar and the altitude is such that the satellite passes over the same latitude at approximately the same local (sun) time each day.

Wavelength. Minimum distance between two events of a recurring feature in a periodic sequence, such as the crests in a wave.

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This publication was produced in recognition that there is a growing need to increasingly transfer land-based/coastal aquaculture production systems further offshore as a result of the expected increases in human population, competition for access to land and clean water needed to increase the availability of fish and fishery products much needed for human consumption. Mariculture, in particular offshore, offers significant opportunities for sustainable food production and development of many coastal communities, especially in regions where the availability of land, near shore space and freshwater are limited. This publication provides, for the first time, measures of the status and potential for offshore mariculture development from a spatial perspective that are comprehensive of all maritime nations and comparable among them. It also identifies nations that are not yet practicing mariculture that have a high offshore potential. The underlying purpose of this document is to stimulate interest for detailed assessments of offshore mariculture potential at national levels.

Remote sensing for the sustainable development of offshore mariculture is included as Annex 3 to this publication in recognition of the importance of remote sensing as a source of data for spatial analyses to assess potential for offshore mariculture, and also for zoning and site selection as well as for operational remote sensing to aid mariculture management.