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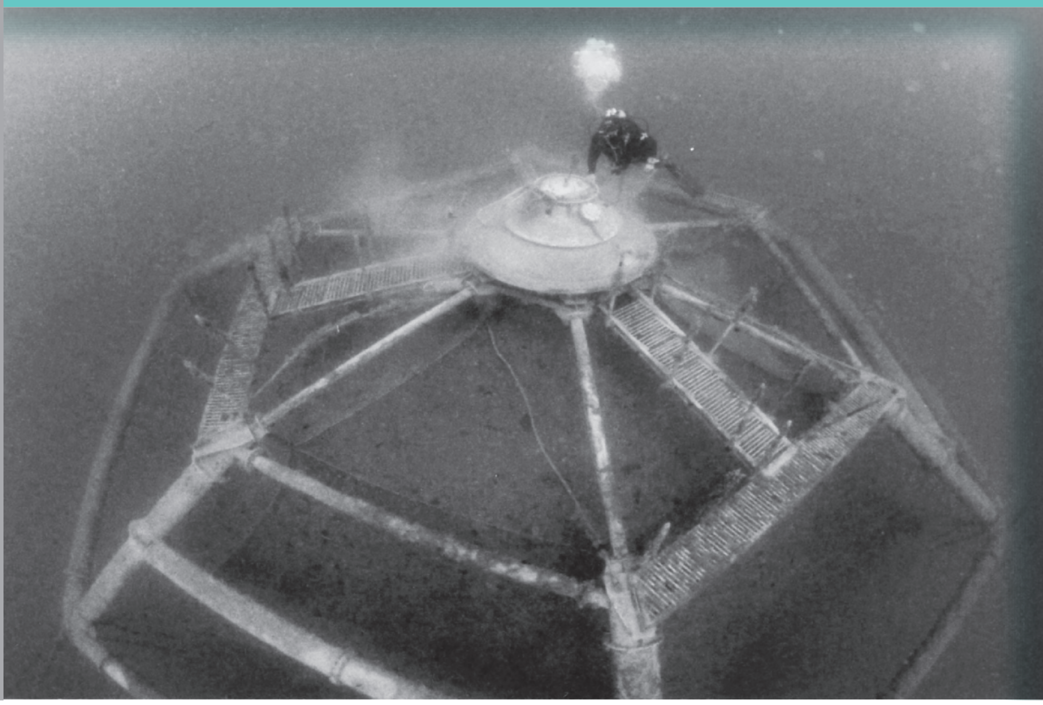
Expanding mariculture farther offshore

Technical, environmental, spatial and governance challenges

FAO Technical Workshop
22–25 March 2010
Orbetello, Italy



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Preparation of this document

This publication is the proceedings of the Food and Agriculture Organization of the United Nations (FAO) expert technical workshop on "Expanding mariculture farther offshore: technical, environmental, spatial and governance challenges", held in Orbetello, Italy, from 22 to 25 March 2010 and organized by the Aquaculture Branch of the Fisheries and Aquaculture Department.

The workshop was attended by 13 internationally renowned experts from eight countries (Canada, Chile, Denmark, Israel, Italy, New Zealand, Norway, the United States of America), representing the private sector, industry, academia, government, research organizations, and eight staff members from FAO.

The focus of this workshop was to discuss the growing need to transfer land-based and nearshore aquaculture production systems farther from the coast as a result of the expected increases in human population, competition and access to land and sea along the coastal belt.

This initiative attempts to collect information on the potential for global mariculture development (off the coast and offshore) by considering technical, biological, spatial, environmental, socio-economic, legal and policy issues and to identify major opportunities and challenges to act upon at all levels for the industry to expand sustainably. Furthermore, it intends to respond to the needs of the FAO Members to ensure access to adequate information on the potential for off-the-coast and offshore aquaculture, as well as, the requirements to fulfil this potential in terms of governance, research, information, investment, capacity building, relevant policies and required strategies at national, regional and global level.

These proceedings are written for national authorities (e.g. governments, ministries, research institutions and the private sector) that are interested in promoting and supporting the development for off the coast and offshore aquaculture, and it attempts to provide a comprehensive review on the main issues specific to this subsector. Furthermore, the recommendations to FAO can also be very useful for consideration by the Committee on Fisheries (COFI) and its Sub-Committee on Aquaculture (SCA) in their deliberations on the increase in global aquaculture output to deliver nutritious food in a sustainable manner.

As an additional output derived from the workshop, the FAO Fisheries and Aquaculture Technical Paper No. 549 entitled "A global assessment of offshore mariculture potential from a spatial perspective" was prepared to provide estimates of quantitative spatial measures of the status and potential for offshore mariculture development. Applications of satellite data for enhanced operational aquaculture management are also described.

The workshop report has been edited by FAO. All the other reviews and case studies have been reproduced as submitted (on the accompanying CD–ROM).

Abstract

This document contains the proceedings of the technical workshop entitled “Expanding mariculture: technical, environmental, spatial and governance challenges”, held from 22 to 25 March 2010, in Orbetello, Italy, and organized by the Aquaculture Branch of the Fisheries and Aquaculture Department of the Food and Agriculture Organization of the United Nations (FAO).

The objective of this workshop was to discuss the growing need to increasingly transfer land-based and coastal aquaculture production systems farther off the coast and provide recommendations for action to FAO, governments and the private sector. The workshop experts proposed general “operational criteria” for defining mariculture activities in three broad categories: (i) coastal mariculture, (ii) off the coast mariculture and (iii) offshore mariculture.

Offshore mariculture is likely to offer significant opportunities for food production and development to many coastal countries, especially in regions where the availability of land, nearshore space and freshwater are limited resources. Mariculture is also recognized as a relevant producer of the protein that the global population will need in the coming decades.

It is likely that species with the highest production today, such as salmon, will initially drive the development of offshore mariculture. Nevertheless, the workshop agreed that additional efforts are necessary to define optimal species and improve efforts in the development and transfer of technologies that can facilitate offshore mariculture development. The workshop discussions and reviews indicate large potential for the development of offshore mariculture although more detailed assessments are needed to determine the regions and countries that are most promising for development. It is also recommended that efforts be increased to farm lower trophic levels species and optimize feeds and feeding in order to minimize ecosystems impacts and ensure long-term sustainability. Similarly, risk assessments and/or environmental impact assessment and monitoring must always be in place before establishing offshore farms, and permanent environmental monitoring must be ensured.

All coastal nations should be prepared to engage actively in developing the technological, legal and financial frameworks needed to support the future development of offshore mariculture to meet global food needs. The workshop report highlights the major opportunities and challenges for a sustainable mariculture industry to grow and further expand off the coast. In particular, the workshop recommended that FAO should provide a forum through which the potential importance of the sea in future food production can be communicated to the public and specific groups of stakeholders and to support its Members and industry in the development needed to expand mariculture to offshore locations.

The proceedings include the workshop report and an the accompanying CD–ROM containing six reviews covering technical, environmental, economic and marketing, policy and governance issues, and two case studies on highfin amberjack (*Seriola rivoliana*) offshore farming in Hawaii (the United States of America) and one on salmon farming in Chile.

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Contents

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Abbreviations and acronyms

AAA	adequate areas for aquaculture
ABNJ	areas beyond national jurisdiction
ACOE	Army Corps of Engineers
ADP	Aquaculture Development Program
AMBI	AZTI's Marine Biotic Index
CCRF	Code of Conduct for Responsible Fisheries
CDUA	conservation district use application
CDUP	conservation district use permit
CITES	Convention on International Trade in Endangered Species of Wild Fauna and Flora
CMBB	Center for Marine Biotechnology and Biomedicine
COFI	Committee on Fisheries
CRAB	collective research on aquaculture biofouling
CWB	Clean Water Branch
CZM	coastal zone management
DA	Department of the Army
DAR	Division of Aquatic Resources
DBOR	Division of Boating and Ocean Recreation
DLNR	Department of Land and Natural Resources
DOA	Department of Agriculture
DOH	Department of Health
EA	environmental assessment
EAA	ecosystem approach to aquaculture
EATIP	European Aquaculture Technology and Innovation Platform
ECASA	Ecosystem Approach to Sustainable Aquaculture
ED	environmental declaration
EEZ	exclusive economic zone
EIA	environmental impact assessment
EPA	Environmental Protection Authority
EU	European Union
FAA	Federal Aviation Authority
FAD	fish aggregating device
FAO	Food and Agriculture Organization of the United Nations
FCR	feed conversion ratio
FDA	Food and Drug Administration (United States of America)
FIFO	fish-in fish-out ratio
FIRA	Aquaculture Branch (FAO)
FOB	freight on board
FONSI	finding of no significant impact
FOSI	finding of significant impact
FWW	Food and Water Watch
GHGs	greenhouse gases
GIS	geographic information system
GMO	genetically modified organism
GPS	Global Positioning System
HAB	harmful algae bloom
HDPE	high density polyethylene
HIHWNMS	Hawaiian Islands Humpback Whale National Marine Sanctuary
HIMB	Hawaii Institute of Marine Biology
HOARP	Hawaii Offshore Aquaculture Research Project

HRS	Hawaii Revised Statutes
ICCAT	International Commission for the Conservation of Atlantic Tunas
ICOAD	International Council for Offshore Aquaculture Development
IIFET	International Institute of Fisheries Economics and Trade
IMTA	integrated multitrophic mariculture
IPN	infectious pancreatic necrosis
ISA	infectious salmon anemia
ITI	infaunal trophic index
IUCN	International Union for Conservation of Nature
KIA	Kona International Airport
LCA	life cycle assessment
MAFAC	Marine Fisheries Advisory Committee
MAFF	Ministry of Agriculture Fisheries and Food
MHC	Marine Harvest Chile
MHI	main Hawaiian islands
MII	Marine Industries and Investments
MMMP	Marine Mammal Monitoring Plan
MOM	modelling–ongrowing fish–monitoring system
NAAFE	North American Association of Fisheries Economists
NACA	Network of Aquaculture Centres in Asia-Pacific
NASCO	North Atlantic Salmon Conservation Organization
NELHA	Natural Energy Laboratory of Hawaii Authority
NGO	non-governmental organization
NIMBY	not in my back yard
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
NWHI	Northwest Hawaiian islands
OCCL	Office of Conservation and Coastal Lands
OECD	Organisation for Economic Co-operation and Development
OFC	off the coast
OFS	offshore
OSHA	Occupational Safety and Health Administration
OTEC	ocean thermal energy conversion
PIRO	Pacific Islands Area Office
PRD	Public Relations Department
R&D	research and development
RAMA	Reglamento Ambiental Para la Acuicultura (Chile)
RFMO	regional fisheries management organization
ROV	remotely operated vehicle
SCA-COFI	Sub-Committee on Aquaculture of the Committee on Fisheries
SCUBA	self-contained underwater breathing apparatus
SEAFDEC	Southeast Asian Fisheries Development Center
TBT	tributyltin
UH	University of Hawaii
UHSG	University of Hawaii Sea Grant Program
UNCLOS	United Nations Convention on the Law of the Sea
UNIDO	United Nations Industrial Development Organization
USDA	United States Department of Agriculture
USFWS	US Fish and Wildlife Service
WET	whole effluent toxicity
WFC	WorldFish Center
WFM	Whole Foods Markets
WG	working group
WHAP	West Hawaii Aquarium Project
ZOM	zone of mixing

Genesis of the workshop

BACKGROUND

Aquaculture is a fast-growing food-producing industry that currently supplies almost 50 percent of the world's food fish and probably has the greatest potential to meet the growing demand for aquatic food. Given the projected global population growth over the next couple of decades, it is estimated that at least an additional 40 million tonnes of aquatic food will be required by 2030 to maintain the current per capita consumption. From an activity that was primarily Asian, aquaculture has now spread to all continents. Furthermore, from an activity that focused on freshwater fish, particularly cyprinids, it now encompasses all aquatic environments and many aquatic species. The present situation, in terms of availability and competition for natural resources, environment protection and population growth, along with advances in biotechnologies, marine engineering, etc., brings with it great potential but also complex challenges in the development of aquaculture.

The rapid expansion of the aquaculture industry has resulted in the demand for more resources (e.g. freshwater, feed) and space to accommodate it. The search for additional areas to expand aquaculture and the identification of new farming species of commercial value to satisfy the growing local and export markets are pushing the sector to expand the mariculture subsector and, in some countries, to expand its activities farther off the coast and offshore where more space is available, where competition is currently less intense, and where environmental impacts from and on aquaculture can be minimized and food safety optimized. As mariculture is offering an ever-increasing opportunity for the sector to expand and become a major supplier of animal protein, a number of issues covering biosecurity, economic, environmental and social aspects will need to be addressed within an ecosystem perspective in order to ensure sustainable growth in the long term.

Despite the global interest in developing mariculture including offshore aquaculture, comprehensive estimates of spatially quantified potential for growth of the industry are scarce. Exclusive economic zones (EEZs), claimed by nearly all countries, are the main areas in which mariculture can expand to the open ocean from present-day operations in sheltered inshore or nearshore areas. Although globally mariculture contributes importantly to overall aquaculture production and value, out of the 145 sovereign nations with EEZs, only 17 of them account for 98 percent of mariculture production. The future contribution of mariculture both for sustainable livelihoods and to provide fish to world markets will be determined, among other factors, by how much area will actually be available for mariculture development among other competing uses and whether farming practices will be truly environmentally friendly, socially sound and economically relevant.

There are also significant knowledge gaps regarding the types of species to be used, the technologies, the environmental issues and the required governance to ensure sustainable offshore mariculture. Finally, FAO requires a global expert perspective to better understand how to further promote and assist offshore mariculture development in all countries where there is the potential.

PURPOSE

The objective of this workshop was to discuss the growing need to transfer land-based and coastal aquaculture production systems farther off the coast and provide recommendations for action to FAO, governments and the private sector.

IMPLEMENTATION AND PARTICIPATION

The workshop took place on 22–25 March 2010 in Orbetello, Italy, and was organized by the Aquaculture Branch of the Fisheries and Aquaculture Department of the Food and Agriculture Organization of the United Nations (FAO). The workshop was attended by 13 internationally renowned experts from eight countries (Canada, Chile, Denmark, Israel, Italy, New Zealand, Norway, the United States of America), and eight staff members of FAO, and covered different core topics and represented different regions of the world. Expertise within this group included the academic, regulatory and consultative sectors of the industry, thus giving a wide perspective of views on the core topics. The list of participants is provided in Annex 2.

Workshop report

PREAMBLE

With the global human population expected to reach 9 billion by 2050, demand for food and feed will substantially increase. The manner in which food and feed production is increased to meet the demand of the world's growing population is a major challenge. Increasing production from the sea through expanded aquaculture may be a better alternative to further land development, which could involve clearing more rain forests, draining more aquifers or using more fertilizers and pesticides as agriculture spreads to marginal lands. Current overexploitation in wild fisheries means that fisheries cannot provide a solution. Expansion of land-based aquaculture and coastal aquaculture faces constraints because of an increasing lack of suitable land and water sites, a dependence on reliable supply of good quality water and, particularly in the coastal zone, the potential for conflicts with other users.

For these reasons, it is believed that the expansion of aquaculture into deeper and farther offshore marine waters is a high priority and should be facilitated through research, development and appropriate regulatory management.

Offshore mariculture offers significant potential for increasing world food production in an environmentally sustainable way. Its expansion is important to achieving the goal of world food security, providing alternatives to wild stock fisheries, and fostering economic development, particularly in coastal regions of the world.

There are potentially significant environmental, economic and food security benefits from the sustainable expansion of mariculture of finfish, shellfish and macroalgae in marine sites that are located farther offshore. However, the achievement of this potential will require, among other things, governments and developmental agencies to work together with the offshore aquaculture industry to develop policy and regulatory frameworks that enable mariculture to move farther off the coast in an environmentally sustainable way. The achievement of this goal also requires policies to facilitate appropriate technological developments.

OBJECTIVES AND APPROACH

The main objective of this technical workshop was to assess the current situation and future prospects for offshore mariculture development around the globe through eight expert reviews. The main output of this workshop was the identification of activities and intervention areas (covering technical, environmental, spatial and governance issues) to be included as components of an FAO action programme in support of offshore mariculture development. The workshop was organized in five main sessions covering technical, environmental, spatial, economics/marketing and policy/governance issues related to offshore mariculture development and focusing on the following themes:

- discussion and agreement on a working definition for offshore mariculture;
- presentation and discussion of the reviews commissioned on offshore mariculture development;
- proposal, discussion and drafting of a series of actions by FAO, coastal States/governments and the industry to address the main issues identified in support of offshore mariculture development.

DEFINITION OF OFFSHORE MARICULTURE

The term offshore mariculture is understood differently among nations and stakeholders, although it clearly refers to farming farther off the coast and in more exposed locations be it in archipelagic waters or the high seas. Nevertheless, the great diversity of coastal waters makes it difficult to define "typical" conditions and it may be challenging to distinguish a farming site that is beyond "coastal".

To facilitate discussions at the workshop, mariculture activity was operationally classified in three categories based on site location (coastal, off the coast and offshore) and then described according to general criteria according to the distance from the coast, water depth, degree of exposure, access to the site and the operational requirements for a farm. However, even these criteria give only a preliminary idea of feasibility, the actual sites, with the prevailing conditions, should always be considered individually.

According to the criteria agreed at the workshop, mariculture is considered "offshore" when it is located > 2 km or out of sight from the coast, in water depths > 50 m, with waves heights of 5 m or more, ocean swells, variable winds and strong ocean currents, in locations that are exposed (open sea, e.g. ≥ 180° open) and where there is a requirement for remote operations, automated feeding, and where remote monitoring of operating system may be required.

WORKSHOP RECOMMENDATIONS

After initial presentations and discussions on a wide variety of topics related to offshore mariculture (see Annex 1), the workshop participants identified eight key issues (not listed in rank order) for the expansion of mariculture offshore. After identifying the issues, the workshop participants were divided into two working groups (WGs), with WG-1 focusing on technical, economic and marketing issues and WG-2 focusing on environmental, policy and governance issues. The two WGs then identified opportunities and challenges and the corresponding actions for FAO to support the development for offshore mariculture for each of the eight issues. The experts' findings are summarized below.

WORKING GROUP 1: TECHNICAL, ECONOMIC AND MARKETING ISSUES

1. Need for enabling governance to facilitate development of aquaculture technologies

Opportunities and challenges – The global increase in fish consumption tallies with trends in food consumption in general. Per capita food consumption has been rising in the last few decades. A self-sustaining mariculture, driven by feed resources mainly taken from outside the human food chain, may increasingly contribute to food supply. Mariculture can also contribute to a reduced pressure on wild stocks. Different coastal States have widely varying plans for developing aquaculture in their coastal waters, and enabling governance can facilitate technological development, leading in time to a realization of mariculture's full potential.

However, there is a general lack of understanding on the potential for offshore aquaculture to contribute to fish output, food security and nutrition in the coming decades. Furthermore, there appears to be a misunderstanding regarding offshore mariculture as if it were equivalent only to farming in areas beyond national jurisdiction (ABNJ), while the potential in areas of national jurisdiction has yet to be fully exploited.

Actions – FAO has a very important role to play in the process of enabling governance that may facilitate development and dissemination of technology among its Members. FAO should give a clear recommendation to Members that, because of global food security, food safety concerns and human nutrition benefits, there will probably be a need to expand mariculture to more exposed waters to increase seafood production. FAO should, in this regard, take the initiative to conduct a cost–benefit analysis of current coastal mariculture versus offshore alternatives considering both farming in the areas of national jurisdiction, where most farming will take place in the coming decades, and in ABNJ.

There is also a need to strengthen national policies and develop international principles for offshore mariculture development, and to include all main stakeholders in this process. Governments of Members should be urged to create and enable policies and regulations to support mariculture and provide other incentives for commercial development.

2. Economic and technological issues associated with a transition from coastal to offshore aquaculture

Opportunities and challenges – The current development of mariculture of species such as salmon (*Salmo salar*), seabream and seabass and experimental/pilot farming of other species such as cobia (*Rachycentron canandum*) and amberjacks (*Seriola* spp.) provides excellent and promising technological advances for moving mariculture farther offshore. However, the economic viability of offshore mariculture is a major challenge and better technologies still need to be developed. There are also concerns about the availability of capital for investments in research and development (R&D) and for the development of commercial farms. Moreover, there is no clear candidate species of finfish available that has proved both economic and physiological feasibility for offshore production and, while species of shellfish and aquatic plants are better identified, the economic viability of their production is still questionable. A transition from coastal to off-the-coast and offshore mariculture will demand the development of new or suitably adapted technologies throughout the value chain, with obvious scientific challenges. This is what is needed if global seafood supply is to be increased in a way that minimizes impacts on benthic and pelagic ecosystems as demanded by society.

Actions – Good access to information on the economics of offshore mariculture can help would-be investors and coastal States in developing economically feasible technologies for offshore mariculture, and FAO can help to provide this. FAO can also help Members by funding demonstration and pre-commercial projects including a variety of species. Member government actions are also needed to create conditions for increased investment in mariculture and to allocate funds for R&D. Governments should also encourage international cooperation and technology transfer among stakeholders.

3. Inadequacy of information on coastal States' interest and opportunities in mariculture development

Opportunities and challenges – The increasing pressure on the use of coastal zones from alternative activities such as tourism and urban development provides strong impetus for aquaculture to move off the coast. However, the interest and capacity of coastal States for developing mariculture in general, and offshore mariculture in particular, is not well known. There may indeed be more interest than generally believed, and access to accurate information on technology, markets and economic potentials may help to clarify the situation. This will require innovations in tools and methods to collect the relevant information from Members, and may contribute to global interaction in general.

Actions – FAO should collect information through surveys to gauge the interest among its Members for developing offshore mariculture. FAO should also assist its Members by identifying logistics and infrastructure that may facilitate developments, provide advice for conducting spatial analyses to estimate potential for offshore mariculture, and also for zoning and selection of sites for development.

4. Ensuring offshore aquaculture sustainability and expansion

Opportunities and challenges – As noted earlier, the growing global human population will require more food, and sustainable and scalable food production in the sea is becoming increasingly important. Aquaculture production, both inland and in coastal zones, is increasingly threatened by pollution and user conflicts, thus opening up an opportunity for offshore mariculture. One of the challenges in doing this is to develop new sources of raw materials for feed that should be, as far as possible, from a lower trophic level than is currently often the case and, preferably, not from sources that serve the existing human food chain. This is necessary if mariculture is to increase its net contribution to the human food supply and not simply to substitute fish for animal products that are now produced on land. A related challenge and benefit in doing this is to ensure that more people can take advantage of the nutritional benefits of seafood production.

Actions – The major recommendations is for FAO to provide advice and guidance to stakeholders and a forum for discussion among them on issues related to global food security, the increasing importance of the sea in future food production and the challenges related to more mariculture activity. Furthermore, FAO should review the sustainability of different food production options, especially offshore mariculture, to set the agenda in terms of research challenges to improve performance of offshore mariculture, but also to guide Members as to relative merits of offshore mariculture in relation to alternative food production options such as forest clearance for agricultural production. This requires participation by both public and private sectors and the creation of conditions that facilitate investments and technology transfer.

WORKING GROUP 2: ENVIRONMENTAL, POLICY AND GOVERNANCE ISSUES

5. The negative image of mariculture (environment and products)

Opportunities and challenges – Aquaculture, in particular mariculture, in some areas of the world has triggered environmental and social concerns, which have influenced the way the public perceives aquaculture. The image of aquaculture is frequently negative across countries and regions, and very often based on the negative impacts of very few commodity species. Moving aquaculture offshore would probably diminish many environmental and food safety risks, if properly conducted. To counteract the negative image of aquaculture, there must be more proactive rather than reactive communication with society. The aquaculture industry and its stakeholders must be more visible and be seen to be socially and environmentally responsible. Removal of negative perceptions takes time, and a paramount premise is transparency and the avoidance of environmental and food safety scandals. The ultimate challenge is to tackle this negative image by clarifying responsibilities with public and political stakeholders, and to make mariculture a prioritized activity in most coastal nations.

Actions – The aquaculture industry and relevant international organizations such as FAO must strive to improve the reputation of the industry among the general public, regulators and policy-makers. The sea will be needed to feed humanity in centuries to come, and it is paramount that this message of global food security and environmental sustainability is clearly communicated to governments by all stakeholders involved. Important aspects in this regard are environmental interactions, use of resources and marine space and food safety. It is also important to communicate that mariculture can help to reduce pressure on commercial fishing and that, by increasing the production of macroalgae as raw material for feed, it may well become a self-sustaining industry.

To improve the image of aquaculture, it is recommended that FAO, through the Committee on Fisheries (COFI) and its Sub-Committee on Aquaculture (SCA), place mariculture on its agenda. Elements of a possible strategy should include the dissemination of widely proven and recognized facts to all involved stakeholders, interaction and discussion with interest groups, be they non-govermental organizations (NGOs), associations or other stakeholder groups, and establishment of frameworks for certification of processes and products. These involve, for example, questions related to feed resources, emission of wastes, species introductions and problems of mariculture escapes.

Governments should promote the sustainable development of mariculture, giving unbiased transparent information to the public and supporting well-managed mariculture actions and actors. It is also vital to establish and fund R&D programmes and to stimulate and support the implementation of education programmes at all levels.

6. Improved understanding of negative and positive interactions between offshore mariculture and the environment

Opportunities and challenges – All food-producing activities and natural resource industries have environmental impacts, and some level of impact must be accepted for mariculture. Furthermore, the fact that aquaculture can have much less impact than other terrestrial sources of protein is a relevant opportunity for the expansion of this sector. It is also important to recognize that mariculture is affected by environmental degradation of coastal and open ocean waters, for example by toxic pollution, which can harm aquatic animals and lead to concerns about food safety. There is generally a poor understanding in society that it is the aquaculture industry itself that becomes the primary victim of environmental degradation. Expansion of mariculture to open waters may reduce this vulnerability because of the greater capacity of such waters to dilute pollutants. For example, the pollution from other sources (including the spreading of disease) becomes less and the impact of aquaculture is more effectively mitigated by natural processes in the benthic and pelagic offshore ecosystems.

There is a general lack of environmental data for potential offshore mariculture locations and of resources for research to provide them, and yet they are essential if offshore mariculture is to be able to validate its promise. This is especially the case in many developing countries, and, therefore, the development and implementation of education and training programmes that can increase the human capacity to undertake environmental assessments is important in all of them.

Actions – FAO must play an active role to inform Members and society in general that mariculture depends on a clean and unpolluted environment, which means, in turn, that a sustainable mariculture industry itself must be environmentally responsible. This calls for action to build awareness of the "two-way" environmental interactions in mariculture.

It is important to develop methods and indicators for estimating carrying capacity of open marine ecosystems, to identify limiting factors and to contribute to establishing guidelines for best environmental practices. Due to the general gap in data from offshore locations, it is important to gather together what data there are and to draw on relevant experience from coastal mariculture. Governments must adopt and implement an ecosystem approach to aquaculture governance and allocate funds to establish the knowledge and build the competence needed to implement it. FAO should strive to promote global sharing of knowledge and experiences gained about the responsible development and management of offshore mariculture among Members.

7. Limited guidance for development of offshore mariculture

Opportunities and challenges – Although there are some useful experiences in culturing finfish, shellfish and macroalgae in exposed off-the-coast and offshore waters in some countries, there is still very little offshore mariculture undertaken anywhere in the world. Therefore, systematic expansion of offshore mariculture around the world still presents many challenges. These include engineering of systems to be able to withstand and be operable in exposed waters, and the identification of suitable areas and species, especially finfish species, that can thrive in offshore conditions and meet consumers' demands for quality and value. These challenges will be particularly large in developing countries.

Actions – Gathering experience and sharing of knowledge is paramount to finding solutions for these challenges, and FAO can play an active part in these processes. Activities may include regional workshops, initiatives in capacity building and provision of guidelines for best practices in offshore mariculture. FAO must also inform and motivate Members to take part in the development of offshore mariculture. A major source of motivation is the importance that mariculture can have for future global food security. Governments need to develop national strategies and work together with FAO on this important issue, and to provide the resources needed to do it. In turn, it is important for the mariculture industry to participate from the very beginning, and to be encouraged to farm shellfish and marine plants by incentives that recognize the environmental benefits of doing so.

8. Enabling policy and regulatory frameworks for offshore mariculture

Opportunities and challenges – Mariculture has relatively limited space for development in most of the world's coastal waters; therefore, there is a growing interest in moving mariculture farther offshore where there is vast potential, fewer competing uses, and space availability is not an issue. Expansion of the mariculture industry can help to meet the growing demands for seafood that cannot be met by fisheries alone. However, at present, there is a general absence of effective governance and regulatory structures to allow for offshore mariculture development, although many countries have suitable locations for offshore mariculture in their national waters. Policy and law-making are sovereign acts, and it may be a challenge in many countries to convince policy-makers of the importance of developing mariculture offshore and to support it, especially in those countries that lack the human and financial capacities for monitoring, control and enforcement.

Actions – FAO should encourage governments to prioritize mariculture as an important food production sector and to create the policies and laws needed to make it happen. Coastal States must take responsibility for leasing space for and monitoring and enforcement of mariculture activities as well as providing incentives for education, research and technology transfer. In addition, there should be incentives to industry for investment in offshore mariculture, including financing, insurance and creation of secure property rights. The industry should be involved in the creation of policy and laws to encourage private development. FAO should also facilitate the establishment of governance instruments needed to enable offshore mariculture development, and ensure that governance becomes ecosystem-based while complying with laws of the sea.

STEPS FOR BROADER ACTIONS

It is clear that production of more food from the sea is needed to feed humanity in the future, so it is of paramount importance to inform governments and all stakeholders about the potential value of off-the-coast and offshore mariculture to address this need. In the same vein, it is also important that they recognize that the expansion of mariculture worldwide will be challenging and, if it is to supplement food from agriculture in a significant way, production must increasingly come from the lowest trophic levels, i.e. filter feeders, aquatic plants and plankton, or through their utilization as feed components for fed aquaculture species. Furthermore, feed sources for fed mariculture must be sustainable and preferably come from the lowest marine trophic level. Specific actions recommended by the workshop participants are as follows:

FAO actions

1. The FAO Committee on Fisheries (COFI) and the COFI Sub-Committee on Aquaculture (SCA) must place mariculture on their agendas.
2. There is a need to expand mariculture offshore to increase seafood production, and FAO must inform and encourage Members to take part in its development. A major motivating factor is the vital role that mariculture will have in addressing global food security in the future. This situation is little understood and recognized in society today, especially in developed countries.
3. FAO should provide a forum through which the potential importance of the sea in future food production can be communicated to the public and specific groups of stakeholders.
4. FAO must guide and support Membes and industry in the development needed to expand mariculture to offshore locations, including the provision of the following services:
    - spatial analyses studies to estimate the potential for sustainable offshore mariculture development, including zoning and site selection;
    - development of funding mechanisms for pre-commercial projects and demonstrations farms;
    - cost–benefit analysis of current coastal mariculture versus the open ocean alternatives;
    - gathering of relevant experience and sharing of knowledge to support the engineering and environmental innovations needed;
    - production of technical publications and other information to support commercial development;
    - provision of technical guidelines for best practices of offshore mariculture;
    - organization of regional offshore mariculture workshops, initiatives for capacity building, and creation of databases to share data and information.
5. Expanding mariculture to offshore locations has major technical and biological challenges. FAO must encourage Members to undertake and guide the research and development that is needed. Available knowledge and expertise from current exposed mariculture activities can be of immense value, especially for those countries that are starting offshore mariculture.
6. FAO must advise governments to consider, whenever technically possible, establishing environmental incentives for integrated multitrophic aquaculture (IMTA) to combine the cultivation of fed aquaculture species (e.g. finfish) with organic extractive aquaculture species (e.g. shellfish / herbivorous fish) and inorganic extractive aquaculture species (e.g. seaweed) to create balanced systems for environmental sustainability (biomitigation), economic stability (product diversification and risk reduction) and social acceptability (better management practices).

7. The real and perceived environmental impacts of mariculture are a major concern to society. FAO must communicate that mariculture depends on a healthy and unpolluted environment and should lead a process to improve the negative image of mariculture in society. Appropriate means for communicating this message are:
   - dissemination of facts to FAO Members, society, and to active groups of involved stakeholders;
   - interaction and discussion with active interest groups;
   - communication of challenges related to the provision of sustainable feed resources, waste emissions, species introductions and problems of escapes;
   - communication of the benefits of mariculture, including the comparative trophic efficiency of aquatic animals and the environmental services that extractive aquaculture can provide.
8. FAO should involve all main stakeholders in developing methods and indicators for estimation of the carrying capacity of different bodies of water and establish guidelines for best environmental practices in open ocean ecosystems that include protocols for food safety and biosecuirity.
9. Governance of mariculture must become ecosystem-based while complying with national and international laws of the sea. FAO should initiate a process to establish international principles and governance instruments needed for undertaking offshore aquaculture in international waters when and if this may take place, although it is recognized that many countries have suitable locations for offshore mariculture in their national waters.

Actions of coastal States/governments

1. Before any progress can be made, governments must be convinced to prioritize mariculture as an important food sector and develop national strategies together with FAO if the organization can be of help. Prioritizing mariculture has to be justified by assessments showing favourable potential. This is needed before moving into more comprehensive policy- and law-making to create and enable policies and regulation regimes to support mariculture.
2. The environment for investment in mariculture, including financing, insurance and creation of property rights in marine waters, must be met by appropriate incentives. Government must create conditions for increased investment in mariculture, and stimulate international cooperation and technology transfer among the stakeholders, i.e.:
   - provide incentives to enable and stimulate domestic and foreign investments in offshore mariculture;
   - direct support to well-managed offshore mariculture activities, including the culturing of shellfish and plants offshore;
   - contribute together with FAO to give unbiased transparent information to society;
   - facilitate technology transfer among producers and supporting industries.
3. Expanding mariculture to offshore locations will require major national and international research, development and innovation efforts, and governments must plan and implement research programmes covering the main challenges in engineering, natural science and social science, i.e.:
   - promote the entire mariculture industry as a cluster for active research;
   - private commercial actors should be encouraged to contribute to the funding;
   - stimulate and support the implementation of education programmes at all levels;
   - support technology transfer.

Actions of the industry

1. The industry must drive the process of expanding mariculture from the very beginning, and should be involved in all aspects of policy-and law-making as far as possible to facilitate the development of sustainable offshore mariculture.
2. The industry must build awareness of both the beneficial and adverse environmental interactions of mariculture while more actively disseminating their activities to society.

Annex 1 – Expanding mariculture farther offshore

A synthesis of the technical, environmental, spatial and governance issues and opportunities

This document provides a synthesis of the main information used as background for the workshop, including the technical papers and case studies presented during the event, as well as relevant points of discussion and technical recommendations from the workshop. This paper was prepared with inputs from the experts that attended the workshop.[1]

1. PROSPECTS FOR MARICULTURE

Aquaculture has been the fastest-growing animal food producing sector in the world for many years. Mariculture, in 2010, made up 30 percent of the global aquaculture production excluding aquatic plants, with 18.1 million tonnes and a value of USD34.4 billion. Mariculture production compares with 77.4 million tonnes harvested by the world's capture fisheries in the same year. The rate of increase in global mariculture production exhibited a pronounced increase as the harvest from fisheries levelled off in the early 1990s. The combined global food harvest from mariculture and fisheries was estimated at 128.3 million tonnes in 2010 (FAO, 2012a), of which, however, 20.2 million tonnes of capture products were destined to non-food uses including fishmeal and fish oil production. This represented an apparent per capita consumption of about 5 g of protein per day, accounting for about 16.6 percent of animal protein and 6.5 percent of total protein consumption in 2009 (FAO, 2012b). In addition, mariculture produced 19 million tonnes of aquatic plants with an estimated value of USD 5.7 billion, accounting for 96 percent of global production including capture fisheries. The majority of aquaculture activities currently take place in developing countries, where aquaculture traditionally has been undertaken in freshwater. However, mariculture is currently increasing, and there is a strong interest in expanding further in several of these countries and in other countries where aquaculture is a relatively new food production sector.

Numerous publications have questioned the ability of humans to feed the world's growing population with nutritious food in the centuries to come, and some have pointed to the opportunity for more effective use of the oceans for producing food through mariculture (Marra, 2005; FAO, 2006; Duarte *et al.,* 2009). The oceans cover some 70 percent of the Earth's surface, and their primary production, mainly undertaken by microscopic phytoplankton, is comparable with that of the terrestrial ecosystem (Field *et al.,* 1998). However, remarkably little food is derived from the oceans, and it could thus be questioned if these immense marine areas can effectively be exploited to help feed humanity in the future (Duarte *et al.,* 2009). Other documents have underscored the technological, environmental and legal challenges and constraints for mariculture development (Diana, 2009). With the uncertain perspectives of global agriculture developments in mind (Miller, 2008) – increasingly driven by environmental concerns – the further exploration of the world oceans to provide food is a discussion item on many international development agendas. The need for such dialogue is further

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[1] This document was prepared with the technical assistance and inputs of Yngvar Olsen (Norwegian University of Science and Technology, Norway).

reinforced in view of the uneven availability and potentially limiting freshwater supply for plant and animal production (CAWMA, 2007). This is further exacerbated by the envisaged effects of climate changes and population growth. Most likely, the further growth in freshwater aquaculture may largely depend on the intensification of pond production, among others, and through the adequate reuse of water. In view of the limitations in freshwater supplies in many regions of the world, Duarte *et al.* (2009) suggest that a self-sustaining mariculture industry could possibly provide a significant proportion of the needed animal protein in the future.

The majority of global mariculture production is undertaken in coastal locations, generally sheltered and characterized by relatively low hydrodynamic energy, shallow waters and proximity to coastal supporting infrastructure. The expansion of mariculture to more exposed waters off the coast is more challenging from a technological, environmental and spatial viewpoint, as well as from a legal aspect. In general, the greater the distance offshore that a mariculture activity is located, in deeper waters and in areas with an increased degree to weather exposure, the higher the degree of technology complexity that will be required, along with greater capital investments. Furthermore, operating costs may also increase.

The increasing pressure on the use of coastal zones from alternative activities such as tourism and urban development provides strong impetus to move mariculture activities of finfish, molluscs and macroalgae into offshore waters. In many countries with well-developed mariculture industries, there is often a growing concern about the capacity of the environment to assimilate wastes in coastal waters, as well as on issues such as disease outbreak and transfer and farmed fish escapees, which may negatively interact with wild fauna and coastal ecosystems as a whole (Tacon and Halwart, 2007). There is also an increasing level of interaction between mariculture operations and other users of coastal waters, at times leading to severe conflicts among key stakeholders. Furthermore, well-organized non-governmental organizations (NGO) have also been successful in influencing public opinion against the proliferation of mariculture activities in coastal waters in many parts of the world, calling for the moving of production farther off the coast.

2. OFF-THE-COAST AND OFFSHORE MARICULTURE: OPERATIONAL DEFINITIONS AND SOME GOVERNANCE IMPLICATIONS

2.1 Criteria for the definition of "off the coast"

The physical diversity of coastal waters, including their topography, hydrodynamic energy exposure and water depths, makes it difficult to define the conditions typical of offshore aquaculture and attempts to do this must be seen as an operational approach rather than an absolute. To facilitate the discussion and move forwards in addressing relevant offshore mariculture issues, the workshop experts proposed a general "operational criteria" for defining mariculture activities. These are grouped in three broad categories, based on the distance from the coast and water depths, thus underlining the degree of exposure, but also according to fish-farm operational requirements and accessibility (Table 1).

According to these criteria, off-the-coast mariculture differs from coastal mariculture primarily by the distance to the coast and the degree of exposure. Coastal mariculture is undertaken in shallow (<10 m) and usually sheltered waters typically <0.5 km from the coast. Off-the-coast mariculture takes place 0.5–3 km from the coast in water depths between 10 and 50 m. The sites can be partly sheltered, but currents are stronger, and wind and wave affect installations more severely than at coastal mariculture sites. Offshore mariculture production is located in areas >2 km, or out of sight, from the coast in water depths >50 m and under the influence of powerful hydrodynamic energy, i.e. waves, ocean swells, ocean currents and strong winds. The term "open ocean" mariculture can include both off-the-coast and offshore mariculture.

TABLE 1
General criteria for defining coastal, off-the-coast and offshore mariculture

Parameters	Coastal mariculture	Off the coast mariculture	Offshore mariculture
Location/ hydrography	· <500 m from the coast · <10 m depth at low tide · within sight · usually sheltered	· 500 m to 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[1] 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	· manual involvement, feeding, monitoring and more	· some automated operations, e.g. feeding, monitoring and more	· remote operations, automated feeding, distance monitoring, system function
Exposure	· sheltered	· partly exposed (e.g. >90° exposed)	· exposed (e.g. >180°)

[1] Hs = significant wave height, a standard oceanographic term, approximately equal to the average of the highest one-third of the waves.

Source: Modified from Muir (2004).

There is a general belief that off the coast and particularly offshore mariculture facilities will require a higher degree of automation and remote control in their operations. Accessibility will depend on weather and waves, but will also depend on the scale and technological level of the farms. Large and advanced offshore mariculture farms in the future may be accessible at all time regardless of weather conditions. It may also happen that staff will live aboard in the control unit of the farms most of the time, as on offshore oil platforms.

The "distance from the coast" criteria can be problematic, however, as it can be understood differently in different circumstances. If "coast" is defined in legal terms as the baseline of the coast, which can be a line connecting fringing islands of the outer archipelago, it follows that coastal mariculture taking place in internal waters (legally defined as inside the baseline; see Figure 1) can be quite exposed (significant wave height [Hs] of up to 3–4 m). Depending on the contour of the baseline, aquaculture activities that take place in internal waters may even be considered as off the coast activities according to the criteria set out in Table 1, if the baseline is set farther away from the coast owing to the presence of distant islands within the sovereign State. This situation is quite typical for the majority of the production locations of Atlantic salmon in northern Europe and in the Chilean fjords. On the other hand, in some other locations, for example along the Mediterranean coast of Spain and Turkey, fish farms can be more than 180° exposed while the distance to the land and water depth can be less than 2 km and 50 m, respectively. In these sites, mariculture has been undertaken for more than 15 years using regular high density polyethylene (HDPE) fish cages. This is certainly a special case as the Mediterranean Sea, a so-called marginal sea, is less influenced by extreme winds. There are other similar situations where mariculture is practised in open bays such as in Sungo Bay (Yellow Sea) off the coast of eastern China, where waters may remain relatively calm even as far out as 5 km or more from the shore owing to the prevailing winds and the orientation of the bay itself with respect to the open sea.

The use of the criteria in Table 1 calls for a careful approach because the term "offshore" can be understood differently and because offshore mariculture locations, according to the above criteria, can be found in internal waters in some countries with extensive archipelagos, as well as on the border of international waters in other countries, and it definitively includes areas beyond national jurisdiction (ABNJ). These criteria can only provide a preliminary idea of the farming conditions and location.

Each farming site, with its prevailing physical and environmental conditions, should always be considered independently.

The basic production principles and technologies for off-the-coast and offshore mariculture remain, however, similar to those of modern coastal mariculture in terms of gear used (e.g. cages), use of dry feeds and selection of the farmed species. The choice of offshore farming sites may, on the other hand, be motivated by different economic drivers. Also, it may be anticipated that there will be a need for more automation and use of more sophisticated and remote-controlled feeding and monitoring systems, as well as the choice of species well suited for offshore mariculture conditions. The farming scale will probably be larger for offshore operations than that in coastal sites, possibly dictated by economic and operational reasons. It may also be speculated that the annual production for an offshore finfish farm could probably be higher than the largest off-the-coast salmon farms of today (e.g. 10 000 tonnes or 2.5 million 4 kg fish per year).

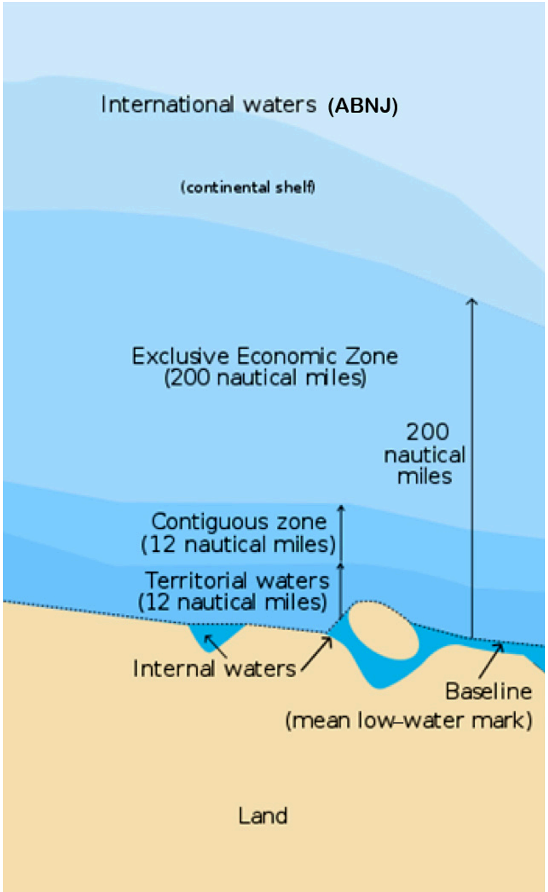
2.2 Some governance implications

Because of the variable coastal topographies, wind exposure and hydrodynamics of coastal countries, there is no unique relationship between the legal grouping of national and international waters of the proposed criteria defined in Table 1. The coastal States have, with few exceptions, the full sovereignty to regulate mariculture activities in internal and territorial waters, extending 12 nautical miles (22 km) from the baseline of the coast. Furthermore, coastal States are also admitted other privileges and responsibilities for utilizing and governing resources within the exclusive economic zone (EEZ) extending to 200 nautical miles (370 km), but there is a legal vacuum regulating mariculture operations in the high seas or ABNJ, leading to a series of potential issues that could arise from such activity. On the other hand, coastal States are obliged to enforce national regulations over any offshore mariculture project at any location in ABNJ conducted by one of their citizens, but not against non-nationals. At the same time, according to the United Nations Convention on the Law of the Sea (UNCLOS), a State is in no position to grant any type of tenure to any portion of the high seas (or ABNJ), provide for the exclusive possession of a farm site, or even grant an effective authority for the use of a particular site.

In contrast to fisheries, there is no specialized body of international law dealing with mariculture. Mariculture is only incidentally affected by aspects of international law that were designed to deal with other issues. Mariculture can be affected by a number of provisions of general international law, such as the developing regime for the protection of the marine environment (Long, 2007) and by treaties. Many treaties create general obligations that can have an impact on state management over mariculture operations, e.g. the 1982 UNCLOS, which requires States to prevent, reduce or control pollution of the marine environment from a number of specified land-based sources (Percy, Hishamunda and Kuemlangan, 2013). Furthermore, many treaties, particularly those that deal with fisheries or the marine environment, can have repercussions on the development of mariculture activities. For example, the Convention for the Protection of the Marine Environment in the North-East Atlantic (OSPAR Convention) has a number of initiatives designed to minimize the impact of mariculture on the marine environment (Long, 2007). Also the 1992 Convention on Biological Diversity (CBD) has potential implications for mariculture (Wilson, 2004) together with codes of practice, whether voluntary or not, such as the FAO Code of Conduct for Responsible Fisheries (the Code) (FAO, 1995).

International law deals with marine activities by placing geographical areas of the sea into a number of categories ranging from internal waters to the territorial sea to the EEZ and, ultimately, to the high seas or ABNJ (Figure 1). Territorial waters and the contiguous zone are included in the EEZ. The coastal State can exercise essentially

FIGURE 1
Generalized sea areas and jurisdiction in international rights



The **baseline** is the low-water line along the coast officially recognized by the coastal State. Straight baselines can alternatively be defined connecting fringing islands along a coast, across the mouths of rivers, or with certain restrictions across the mouths of bays.

Intemal waters are defined as waters landward of the baseline, over which the State has complete jurisdiction; not even innocent passage is allowed. Lakes, rivers and archipelagic waters within the outermost islands are considered internal waters.

A State's **territorial sea** extends up to 12 nautical miles (22 km) from its baseline. The State has sovereignty over its territorial sea, but ships from all nations have the right of friendly passage.

The **contiguous zone** is a band of water extending from the outer edge of the territorial sea to up to 24 nautical miles (44 km) from the baseline, within which a State can exert limited control as in the territorial sea.

An **exclusive economic zone** (EEZ) extends from the outer limit of the territorial sea to a maximum of 200 nautical miles (370.4 km) from the territorial sea baseline, thus it includes the contiguous zone. A coastal State has control of all economic ressources within its EEZ.

The **international waters (or high seas; ABNJ)** are oceans, seas and waters outside of national jurisdiction.

Source: Modified from UNCLOS (1982).

the same rights of sovereignty over its internal waters as it does over land, and this includes mariculture activity. The same appears to apply also for the territorial sea, but some international obligations are involved, including the right to passage by ships. Restrictions on mariculture activities in territorial waters are imposed when these threaten commercial navigation. The coastal State is entitled to legislate in order to protect facilities and installations, including mariculture installations, within the territorial sea, but it must give due publicity to its laws and regulations (1982 UNCLOS, Art.21[4]). International law does not impose other general restrictions on how the coastal State manages mariculture within the territorial sea.

The sovereign rights to manage natural resources undoubtedly allow coastal States to establish, protect, regulate and manage mariculture operations in the EEZ. The international interest in the EEZ has, however, placed additional obligations on those rights where the conduct of the State might affect the EEZ of neighbouring States or international waters/ABNJ. Those obligations take two principal forms that deal with pollution control and the management of straddling and highly migratory fish stocks. The sovereign rights of the coastal State within the EEZ are accordingly limited where they have an impact on highly migratory fish stocks (Articles 63 and 64 of the UNCLOS). These articles gave rise to an agreement commonly known as the Fish Stocks Agreement (1995) (U.N. Doc. A/CONF.164/37). It has commanded a high degree of support and places several obligations on the parties that can have an impact on the conduct of mariculture activities within the EEZ. It addresses a number of issues that are often controversial in the management of mariculture, including minimizing waste discards, impacts on fish stocks, and protection of biodiversity in the marine environment.

Article 56 [1][b][iii] of the 1982 UNCLOS treaty states that, within the EEZ, coastal States have jurisdiction with regard to the protection and preservation of the marine environment. Even for principles that are not legally binding, such as the principle on sustainable development and the precautionary approach as dictated in the Rio Declaration, they place a constraint on coastal States when exercising their sovereign rights under Article 56. States can permit mariculture activities, but in a manner that ensures sustainability (Percy, Hishamunda and Kuemlangan, 2013).

The potential for offshore mariculture activities to do significant harm to the ABNJ environment remains a key question and an important issue of discussion. At present, there is very little scientific documentation and evidence on adverse environmental impacts on pelagic communities and/or benthic ecosystems from offshore mariculture activities. However, as an increasing number of farming activities move farther offshore, in deeper and more exposed waters, more information is being gathered on the impacts, allowing a better understanding of the interaction of farming structures and operations and the environment as a whole (Holmer, 2013; Angel and Edelist, 2013).

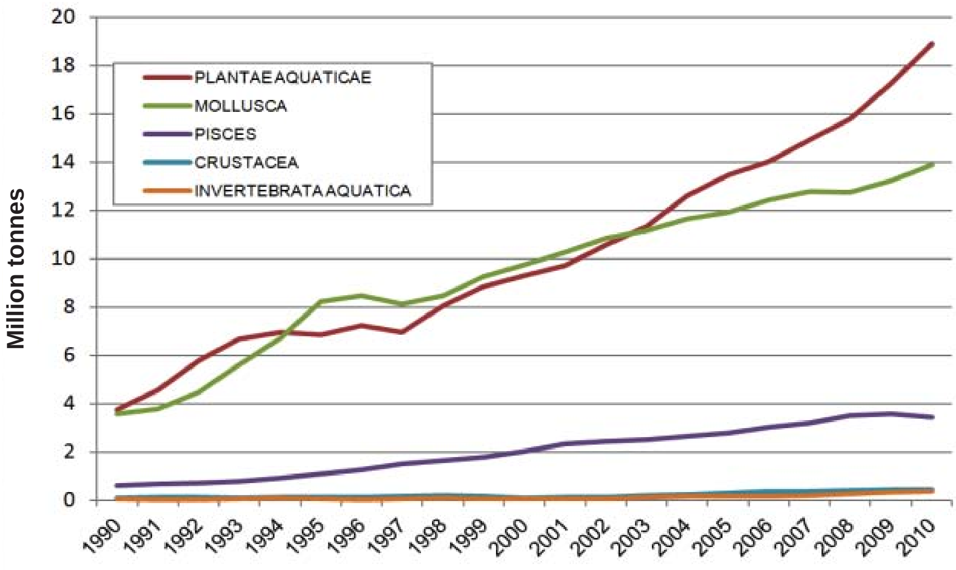
Nevertheless there is a large, unrealized potential for offshore mariculture within EEZs (Kapetsky, Aguilar-Manjarrez and Jenness, 2013), and, most probably, in the coming decades, aquaculture will grow mainly in such areas.

3. STATUS OF GLOBAL MARICULTURE PRODUCTION

3.1 Production and value

Global marine aquaculture production trends for the main species groups show a rapid and steady increase for marine plants (macroalgae) and molluscs in recent decades, whereas finfish and crustaceans exhibit a somewhat slower, although steady, rate of increase (Figure 2). Macroalgae, in particular, are the fastest growing product category over the past decade. Except for crustaceans, which are produced in coastal and inland ponds, the majority of production is undertaken at sea, and the species farmed are candidates for offshore mariculture.

FIGURE 2
Trends in marine aquaculture production, 1990–2010



Source: Global dataset of aquaculture production (quantity and value) 1950–2010. Fisheries and Aquaculture Statistics and Information Service, FAO (extracted August 2012).

TABLE 2
Production and value of the main marine aquaculture products in 2010

Species groups	Total production (tonnes)	Production (%)	Value ('000 US$)	Value (%)	US$/kg
Macroalgae	18 904 903	46	5 602 095	14	0.30
Molluscs	13 881 384	38	13 948 008	35	1.00
Crustaceans	442 467	1	1 969 966	5	4.45
Finfish	3 427 418	9	17 427 942	44	5.08
Others	385 005	1	1 010 535	2	2.62
Total	**37 041 176**	**100**	**54 803 761**	**100**	**1.08**

Source: Global dataset of aquaculture production (quantity and value) 1950–2010. Fisheries and Aquaculture Statistics and Information Service, FAO (extracted August 2012).

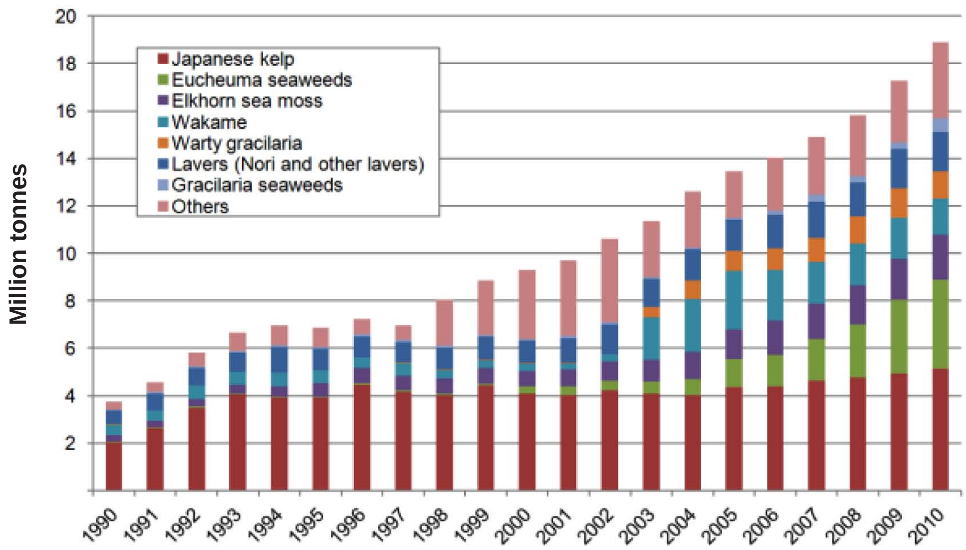
Table 2 summarizes global marine culture production for 2010 by main species groups. It shows that most production by weight (84 percent) consisted of macroalgae and molluscs, and that finfish and crustaceans had the highest unit values (79 percent).

3.2 Production of dominant marine aquaculture species

The main species groups are dominated by a few species. Japanese kelp (*Saccharina japonica*) is dominant among the macroalgae and made up 27 percent of the plants that were farmed in 2010 (Figure 3). The total production of macroalgae has increased from 2003 to 2010, and a number of subdominant species are now also being produced in quantities of more than 1 million tonnes, as reported in 2010.

The Pacific cupped oyster (*Crassostrea gigas*) and the Japanese carpet shell (*Ruditapes philippinarum*) were the two main mollusc species produced by marine aquaculture in 2010, accounting for 31 and 26 percent of farmed molluscs, respectively (Figure 4). Several other mollusc species were produced in quantities of more than 100 000 tonnes in 2010 and have exhibited a steady increase in production in the past two decades. In particular, the production of constricted tagelus (*Sinonovacula constricta*) has expanded rapidly since 1990. As regards farmed crustaceans, white leg shrimp (*Litopenaeus vannamei*) was the dominant cultured shrimp species in marine aquaculture, accounting for 78 percent of farmed crustaceans in 2010 (Figure 5). Swimming crabs (*Portunidae*) accounted about 21 percent of farmed crustaceans. Production of other crustacean

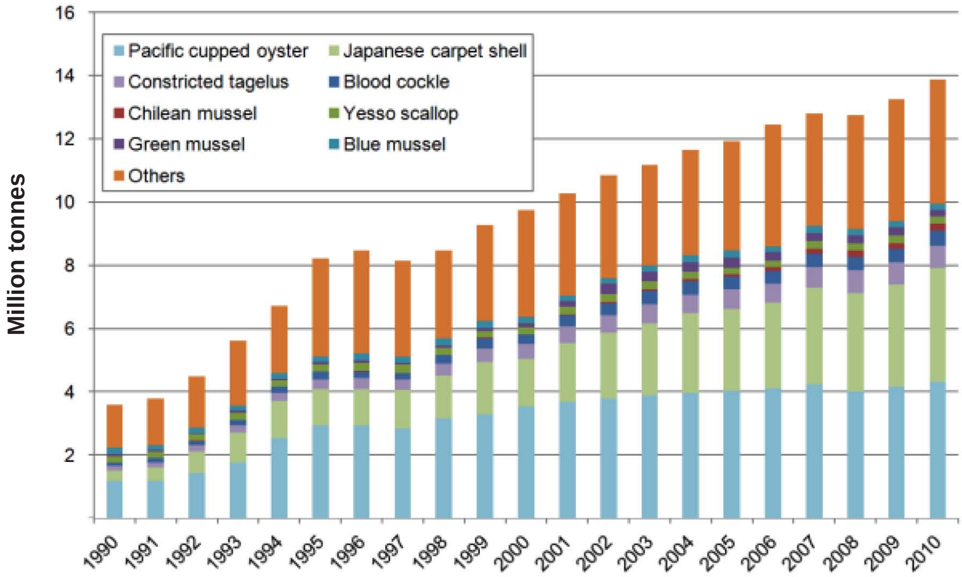
FIGURE 3
Top farmed marine plants in marine aquaculture



Source: Global dataset of aquaculture production (quantity and value) 1950–2010. Fisheries and Aquaculture Statistics and Information Service, FAO (extracted August 2012).

FIGURE 4

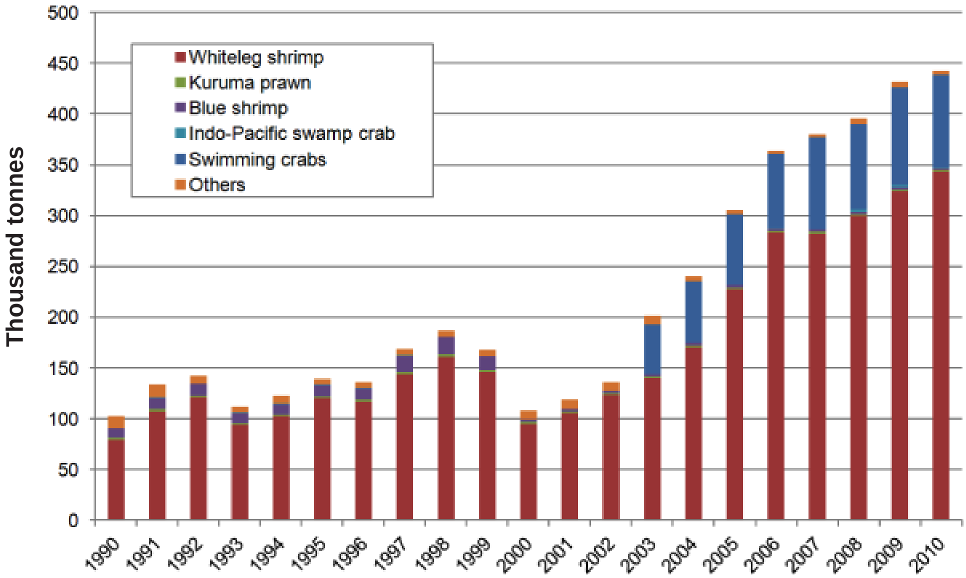
Top farmed molluscs in marine aquaculture



Source: Global dataset of aquaculture production (quantity and value) 1950–2010. Fisheries and Aquaculture Statistics and Information Service, FAO (extracted August 2012).

FIGURE 5

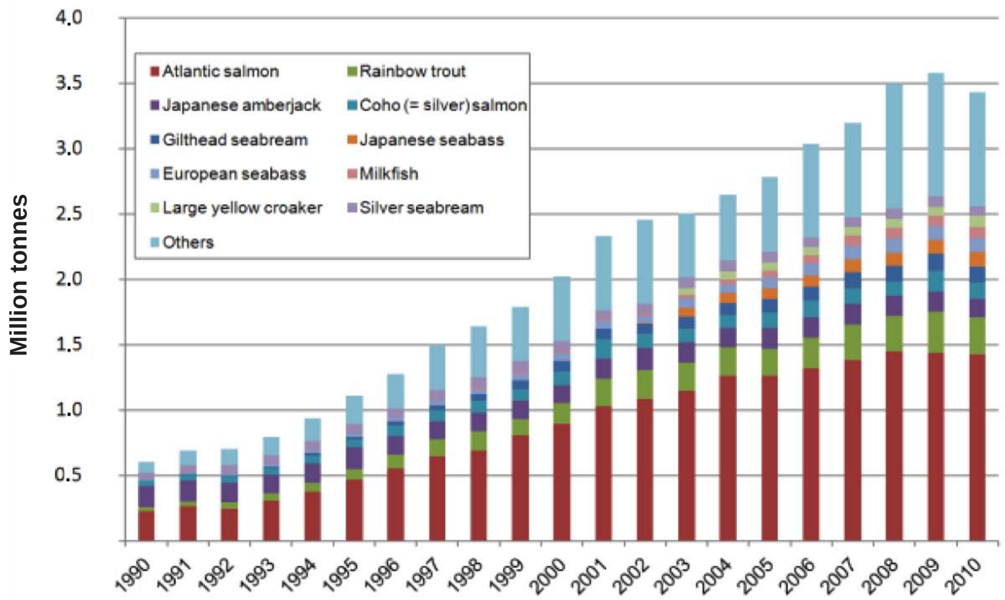
Top farmed crustaceans in marine aquaculture



Source: Global dataset of aquaculture production (quantity and value) 1950–2010. Fisheries and Aquaculture Statistics and Information Service, FAO (extracted August 2012).

species, mostly prawns and spiny lobsters, was quite limited in quantity. Atlantic salmon (*Salmo salar*) made up 41 percent of the finfish farmed in marine aquaculture in 2010 (Figures 6) followed by rainbow trout (*Oncorhynchus mykiss*), accounting for 8 percent. While the production in quantities was limited, some finfish species, including several groupers, reached a high unit value.

FIGURE 6
Top farmed finfish in marine aquaculture



Source: Global dataset of aquaculture production (quantity and value) 1950–2010. Fisheries and Aquaculture Statistics and Information Service, FAO (extracted August 2012).

3.3 Candidate species for offshore mariculture

The primary drivers of species success in aquaculture are biological and behavioural adaptability to farm conditions, and the market attributes of the final product, including:

- they have many human health benefits and/or they have value as a food ingredient, and for the extraction of desired substances;
- they are demanded in the market and adequately priced compared with their production costs;
- they have high tolerance for farming conditions, including handling and crowding, ready acceptance of artificial feeds (for fed species) and perhaps also have natural resistance to parasites and disease;
- they have readily available seed stock, either from hatcheries or natural settlements;
- they exhibit fast or relatively fast growth;
- they have the adaptability to be farmed outside, as well as within their native range;
- they have been, in some cases, genetically improved by selective breeding, extending their advantages even further over new candidate species;
- they have edible meat yields that allow the production of economically attractive value-added products.

Evidence so far shows that only a few of the species that are presently farmed have the characteristics required to become a major farmed species. If, for example, "major" is defined as exceeding 1 million tonnes per year of production, only one farmed finfish species meets this definition, namely, Atlantic salmon, which completely dominates the finfish product category (Table 3). There are four major seaweed species, with Japanese kelp dominant, one major mollusc species, Japanese carpet shell and one major crustacean species, white leg shrimp.

TABLE 3
Production and value of the major species in marine aquaculture reported in 2010

Common name	Scientific name	Production (tonnes)	Production[1] (%)	Value[1] (US$)	Value (%)
Marine plants					
Japanese kelp	*Saccharina japonica*	5 146 883	27	300 868	5
Wakame	*Undaria pinnatifida*	1 537 339	8	666 865	12
Warty *Gracilaria*	*Gracilaria verrucosa*	1 152 108	6	342 092	6
Laver (Nori)	*Porphyra tenera*	564 234	3	1 095 015	20
Molluscs					
Japanese carpet shell	*Ruditapes philippinarum*	3 604 247	26	3 353 640	24
Pacific oyster	*Crassostrea gigas*	4 305 342	31	3 411 877	31
Shrimp					
White leg shrimp	*Penaeus vannamei*	343 206	78	1 499 100	76
Finfish					
Atlantic salmon	*Salmo salar*	1 422 715	42	7 792 644	45
Rainbow trout	*Oncorhynchus mykiss*	287 319	8	1 835 892	11
Japanese amberjack	*Seriola quinqueradiata*	139 077	4	1 187 923	7

[1] Production (%) and Value (%) indicate the proportion of each species representing in the total production of individual taxonomic group in 2010.

Source: Global dataset of aquaculture production (quantity and value) 1950–2010. Fisheries and Aquaculture Statistics and Information Service, FAO (extracted August 2012).

Most species that are suited for coastal mariculture will probably be suitable also for off-the-coast mariculture, whereas it is likely that a smaller group of species will be best suited for offshore mariculture. Crustaceans, or shrimps (which dominate that group), are mostly grown in coastal ponds in the tropics and are not commonly reared in sea-based aquaculture, be it in coastal mariculture, off the coast or offshore mariculture.

The economic interest of offshore mariculture is today primarily related to finfish, but only one species among the “million tonne/year” is a finfish species (see Table 3). Atlantic salmon technology for cage farming is highly developed and economically feasible, but the commercially strong and well-developed salmon companies have so far not led the process of moving production to offshore mariculture locations. There is some doubt about the biological suitability of on-growing salmon in very dynamic offshore waters, and the availability of protected and semi-protected locations has been sufficient to meet production needs up until now. Off-the-coast locations have, however, for a long time been used for on-growing of salmon, and there is recently an emerging trend of moving salmon farms to more exposed production locations, at least in some regions owing increasing environmental pressure on salmon farming, as well as to reduce the occurrence of diseases and parasites (e.g. sea-lice).

There are perhaps no other obvious candidates for offshore mariculture among the other finfish species produced in quantities <200 000 tonnes/year. Table 4 reviews some finfish species that are generally believed to be suited for production in highly dynamic waters and their current state of production. Most of these candidates are currently grown in temperate waters. The required knowledge on the biology and husbandry techniques, along with commercial experience, is currently adequate for some seabream and amberjack species, but still moderate or insufficient for others such as cobia and a number of snapper species. This means that any farming initiatives taken must engage a strong R&D element. Furthermore, the current economic and organizational abilities of the mariculture industry to take unproven species to commercial production in offshore mariculture waters are rather limited, indicating that such offshore developments are likely to take some time.

Mussels, scallops and macroalgae are extractive organisms, and this fact facilitates cultivation in harsh environments. Off-the-coast and offshore mariculture of blue mussels and other mussel species have been tested in the Mediterranean, Atlantic Canada, New Zealand and northeastern United States of America. Many species of

TABLE 4
Brief review of finfish species (excl. Atlantic salmon) potentially suitable for offshore mariculture and their current mariculture production status

Common name (Scientific name)	2007[2]		2011[2]	
	Production (tonnes)	Value (USD)	Production (tonnes)	Value (USD)
Cobia (*Rachycentron canadum*) (De Silva and Phillips, 2007; Benetti, Clark and Feeley, 1999; Liao, 2003; O'Hanlon *et al.,* 2003; Benetti *et al*., 2003)	29 869	56 929	40 863	66 258
Snappers[1] (red snapper, *Lutjanus campechanus*, and mutton snapper, *Lutjanus analis*) (Benetti *et al*., 2006; Benetti, Clark and Feeley,1999; Benetti *et al*., 2002; O'Hanlon *et al*., 2003; Rotman *et al*., 2003; Bridger, 2004; Bridger *et al*., 2003)	16	65	520	3 043
Red drum (*Sciaenops ocellatus*) (Bridger, 2004; Bridger *et al*., 2003)	51 819	65 669	67 339	91 877
Amberjack species (*Seriola* spp.) (e.g. greater amberjack, *Seriola dumerili*, and Japanese amberjack, *Seriola quinqueradiata*) (Benetti, Clark and Feeley, 1999; Corbin, 2006; Rotman *et al*., 2003)	172 548	983 233	160 477	1 398 378
Gilthead seabream (*Sparus aurata*)	124 637	710 838	154 820	928 934

[1] All cultured snapper species are included; mangrove red snapper (*Lutjanus argentimaculatus*) is dominant.

[2] Global dataset of aquaculture production (quantity and value) 1950–2012. Fisheries and Aquaculture Statistics and Information Service, FAO (extracted August 2013).

macroalgae that naturally grow in exposed coastal areas are probably well suited for offshore mariculture as long as there are enough nutrients and organic matter as natural feed. For example, Japanese kelp, a "million tonnes/year" species is cultured in large amounts in open waters in Sungo Bay in China.

Species selection is a major issue of concern as mariculture moves to more exposed locations. Some general questions about mariculture species selection for the future are:

- Is the current pattern of only a few successful species (see Table 3) accidental or is it because, as in agriculture, only a few species have special attributes that make them self-selecting?
- Are there mariculture species with the right characteristics that are waiting to be "discovered" for offshore mariculture?
- If very good species for offshore mariculture are limited in number, will it be necessary to transfer those that are good farther afar from their natural range? If so, what precautions are needed?

Some of the main factors slowing down development for offshore mariculture of finfish in tropical regions have been: (i) no well-established commercial mariculture activity of finfish species that would also be suitable for offshore mariculture; (ii) no developed mariculture onshore infrastructure that could support further developments into offshore mariculture; and (iii) high production costs. Consequently, the development of offshore mariculture farming technology has had to contend with developing culture methods for largely unknown aquaculture species simultaneously with developing new farming technology and infrastructure. This contrasts significantly with the development of off the coast mariculture, which has mostly consisted of advancing mariculture infrastructure for existing and well-established aquaculture species. It is likely that because of the high production costs, only a few species can be economically viable for offshore mariculture.

In temperate waters, there is more extensive commercial aquaculture in exposed locations farther from the coast for the mariculture of seabream and salmonids, but for salmon, however, producers have shown little interest to move into offshore mariculture. This limited interest relates to, among other things, a relatively good availability of sites for expansion in more protected areas and the interest for the industry to improve commercial returns through other less risky developments, such as improving husbandry, feed formulation, feed delivery and localization. Despite this, salmon farming in central Norway has, for example, found great economic incentives for moving farther from the coast by increasing the cage size and improving the infrastructure and logistics of the fish farms.

At present, however, even though the economic predictions from economic modelling studies presented in Table 5 are uncertain, a number of commercial or pilot-scale offshore mariculture activities for shellfish and finfish farming have progressed in tropical and temperate waters during the last decade, and further new initiatives are developing.

A high number of marine animals and plants have been farmed over a short time (Duarte, Marbá and Holmer, 2007), but few species as mentioned above are produced in large quantities. The evidence from recent years suggests that the concentration on a few species, and only a few "million tonnes/year" species, may not be fortuitous. There is a need for a careful examination of species selection for offshore mariculture, especially for those species where there are high expectations of their potential for

TABLE 5
Economic modelling studies for offshore mariculture production of finfish and shellfish

Species/group	Location and culture systems	Result (Economic viability)	Authors
Sea scallops (e.g. *Placopecten magellanicus*) and blue mussel (*Mytilus edulis*)	New England (USA); longline and seabed production.	With potential to be economically viable. Seabed seeding was most promising for scallop culture. Commercial mussel culture using submerged longlines was found to be economically viable and provided a sufficiently high market price. High risks of crop loss because of fouling and extreme weather conditions; significant initial capital investment was needed.	Hoagland, Kite-Powell and Jin (2003) Kite-Powell, Mogland and Jin (2003) Kite-Powell *et al.* (2003)
Mussels	Canada; longlines.	Not economically viable, due in large part to the slow growth of the shellfish in the cold waters.	Bonardelli and Levesque (1997)
Mussels, e.g. *Perna canaliculus*	New Zealand; longlines.	Offshore mariculture production was concluded to be marginal at best. Assessment studies were made by private mariculture companies in New Zealand, which operate some of the most efficient large-scale mussel farming systems in the world.	
Cobia (*Rachycentron canadum*), red snapper (*Lutjanus campechanus*), and red drum (*Sciaenops ocellatus*)	Gulf of Mexico; cage culture.	Economic modelling indicated that offshore mariculture of cobia, red snapper and red drum were unlikely to be economically viable unless the scale of the farm increased, landed prices increased and stocking densities were very high. Cobia showed the greatest potential.	Posadas and Bridger (2003)
Finfish species; cod, salmon and flounder	New England (USA); cage culture.	Modelling suggested that it would be economically viable, indicating the importance of the distance from shore, feed cost and maximum stocking density. Significant costs were associated with operating and maintaining cage systems, vessels, and staffing, emphasizing the importance of automation.	Kite-Powell *et al.* (2003)
Gilthead seabream (*Sparus* sp.)	Canary Islands (Spain) and the Mediterranean; cage culture.	Ongoing production activities are economically viable. Variable costs, i.e. feed and labour, made up approximately 50 percent of total costs, fixed costs were approximately 13 percent. The most economic scale was a large farm of 48 000 m^3. Financial returns were most sensitive to mortality, feed use and the commercial price for final product.	Gasca-Leyva *et al.* (2002) Gasca-Leyva, Leon and Hernández (2003a) Gasca-Leyva, Leon and Hernández (2003b) Gasca-Leyva *et al.* (2003)
Mutton snapper (*Lutjanus analis*)	Puerto Rico; cage culture (Ocean Spar SeaStation).	Could be profitable provided that the scale of production was increased significantly to reduce labour costs, and that the cost of the farming technology was lower.	Brown *et al.* (2002)
Atlantic salmon (*Salmo salar*)	Fish cage culture.	Production reached 1.4 million tonnes in 2011. Concluded to be economically viable for offshore, although this conclusion has often been questioned.	Ryan (2004) James and Slaski (2006) FAO (2012a)

future major increases in mariculture production. If the long-term goal for marine aquaculture is to fill an expected seafood deficit of many millions of tonnes per year, it may be necessary to focus on a few species that have demonstrably superior culture characteristics.

Finally, considering biosecurity requirements, a reasonable proposition may be that all new mariculture activities are to be based on only native marine species, but this may be unrealistic. It is noteworthy that all the "million tonnes/year" species in Table 3 are already farmed widely outside their native range. This poses a major challenge, and proper risk assessment and risk management must be in place in such new operations.

4. OPPORTUNITIES, TECHNICAL CONSTRAINTS AND FUTURE NEEDS OF OFFSHORE MARICULTURE

Offshore waters are generally more exposed to wind and waves, and therefore, require more advanced aquaculture technology and infrastructure in order to remain effective. Two approaches have emerged. First, there is the evolution of existing commercial mariculture technologies mostly through more robust construction of coastal mariculture systems making them suitable for offshore waters. These mariculture systems are being increasingly commercialized, with the higher infrastructure and operating costs offset by greater scale of production and the increased use of remote control technologies. Second, there is the development of novel offshore water mariculture technologies, which mostly involve large-scale structures that can be submerged to avoid the wind and wave exposure encountered in offshore situations. While many of these novel mariculture systems are only in the design stages or are being operated on an experimental basis, an increasing number are coming into commercial-scale production.

Most of this technological and commercial development is occurring in the cooler water regions of the world, where the majority of large-scale commercial mariculture production currently occurs, especially for finfish. However, there is significant potential for the development of mariculture in the world's tropical zone, with many countries within this zone now actively encouraging mariculture development. There are some examples of companies taking advanced commercial mariculture technologies, including open water technologies, into the tropical zone. In general, the tropical region of the world's oceans provides some significant advantages for aquaculture. Most importantly, the waters are warm and usually with a limited seasonal fluctuation, which can deliver very fast growth rates in species suited to these conditions. Advanced knowledge and greater experience of suitable tropical finfish species, such as cobia (*Rachycentron canadum*), will provide a stronger basis for advancing open-water mariculture in the tropical zone. Further advances could be achieved for developing nations in the tropical zone by encouraging the improvement of mariculture governance and planning, as well as assisting with technological and personnel capability in open-water mariculture. It is recommended that these areas should be the focus of future international initiatives in collaboration with developing nations.

4.1 Available technology and engineering for mariculture and the potential for offshore

Although culture methods for finfish, shellfish and macroalgae are quite different, the challenges of anchoring and operating at sea are common to all and there is a general need for engineering sophistication in the offshore environment. Important considerations include: (i) heavy-duty moorings in deep water; (ii) offshore systems for the containment of the aquatic crops; (iii) sea-going work boats fully equipped with cranes and crop harvesting and handling equipment; (iv) offshore feed storage and feed distribution systems; (v) automatic or partly automated feeding systems; (vi) mechanization as far as possible of all husbandry and maintenance tasks; (vii) remote monitoring and control systems; and (viii) development of large farms in order to generate economies of scale.

Offshore mariculture requires different or more sophisticated production technologies from those used in more protected areas. Some salmon farms are currently located in waters characterized by relatively high hydrodynamic energy, using HDPE cages located in off-the-coast locations. Although the farming technology developed for these salmonids is leading the development of finfish mariculture at the global level, it cannot be completely adopted for offshore mariculture, but many of the farming principles and components of these systems can, and these are being further developed to sustain offshore mariculture conditions.

A very wide range of designs and concepts have been promoted for finfish mariculture (Beveridge, 2004). A large number of these evolved from offshore oil and gas rigs, and some have promoted the use of adapted petroleum infrastructure (Hanson, 1974a; Hanson, 1974b; Ribakoff, Rothwell and Hanson, 1974; Stickney, 1997). These include bottom-supported platforms, such as the Texas towers, jack-up rigs and monopods, floating and semi-submersible platforms, including modified conventional ships and barges, as well as net pens supported between moored spar buoys. Fredheim and Langdan (2009) have published a comprehensive paper summing up recent advances in technology for off-the-coast and offshore finfish farming.

A frequent approach to overcoming the problem of wave stresses on offshore farming equipment has been to enclose and submerge the infrastructure either permanently or during periods of adverse weather conditions. This results in decreased stress on the infrastructure itself as water particle motion decreases exponentially from the sea surface to zero at a depth corresponding to half the wave length (Beveridge, 2004). In addition, submerging fish cages has the added advantage of avoiding or reducing conflicts with other water users, such as boat traffic. It can also help in avoiding surface jellyfish swarms and damage from collisions with floating debris (Beveridge, 2004; Ryan, Jackson and Maguire, 2007).

A large variety of offshore cages have been devised, built, tested and to some extent commercialized over the past 30 years or more (Beveridge, 2004). However, it appears that some submerged and semi-submerged cage designs are beginning to emerge as the most likely types to be commercialized more widely. The semi-submersible Farmocean sea cages (www.farmocean.se) were designed in Sweden and first used in 1986 and are now widely used, especially in Europe and the Mediterranean (Beveridge, 2004; Scott and Muir, 2000).

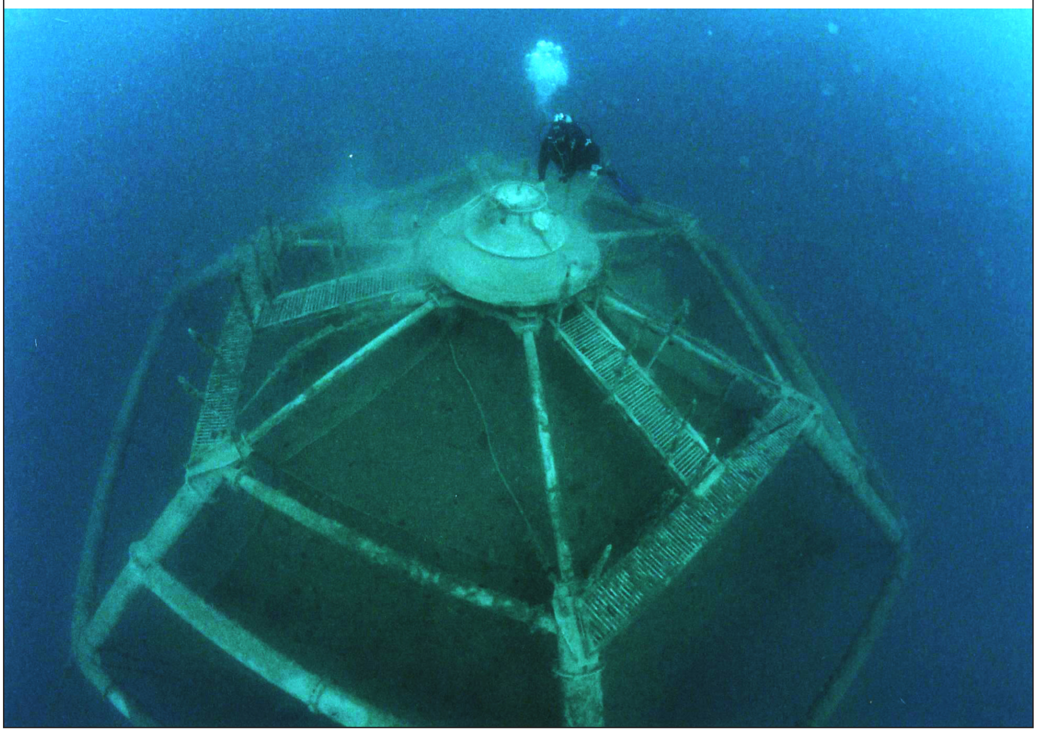
Submersible off-the-coast cages that have been widely used, especially in tropical regions of the world, are those produced by OceanSpar (www.oceanspar.com) (Baldwin *et al*., 2000; Halwart, Soto and Arthur, 2007; James and Slaski, 2006) (Plate 1). OceanSpar cages have been used in Hawaii (the United States of America), Puerto Rico, Bahamas, in the Gulf of Mexico, Cyprus and New Hampshire (the United States of America). The Sadco-shelf is a rigid hexagonal cage design constructed of tubular steel that is fully submersible (www.sadco-shelf.sp.ru) (Ágústsson, 2004; Beveridge, 2004) (Plate 2). In the submerged position, the cage is reported to withstand waves over 15 m in height and current speeds in excess of 1.5 m/s. The main drawbacks of these farming structures are the initial high capital investment needed and the requirement for generally costly diver servicing. Furthermore, it has been noted that they still need to be fitted with more efficient feeding systems (Ágústsson, 2004; Halwart, Soto and Arthur, 2007; James and Slaski, 2006; Scott and Muir, 2000).

Several other robust submersible sea cages are available on the market that have been developed in Asia (China and Taiwan Province of China), including one specifically designed for farming flatfish with multiple bottom layers to facilitate the bottom dwelling behaviour of the cultured flat fish (Chen *et al.*, 2007; Chen *et al.*, 2008; De Silva and Phillips, 2007; Guo and Tao, 2004; Xu, 2004).

PLATE 1
Subsurface view of single-rim SeaStation

COURTESY OF OCEANSPAR LLC

PLATE 2
A fully submersible Sadco-Shelf E-Series rigid hexagonal cage with self-contained underwater feeding system



COURTESY OF SADCO SHELF LTD

In terms of bivalve aquaculture, commercial activities off the coast use the longline technology originally developed for nearshore farming operations, but with the utilization of stronger and heavier gear. However, the use of this technology in offshore waters remains problematic as a result of the increased strain loads of farm infrastructure, particularly during large wave conditions (Merino, 1997). In addition, the increased vertical movement in the farming structure due to wave motion can result in the detachment of the farmed stock such as for mussels that rely on byssus threads for their attachment to the farming structure. Lovatelli (1988) described in detail the structures used for the suspended farming of the Yesso scallop (*Pactinopecten yessoensis*) in Mutsu Bay in northern Japan using submerged longlines from which netting containers are hung and in which the scallops are cultured. Longline systems are adaptable to different farming situations and are well suited for growing crops that attach directly to ropes such as mussels and some macroalgae. Consequently, they have been adapted for offshore mariculture of mussels in the Mediterranean, Yellow Sea, North Sea, Atlantic Canada, New Zealand and northeastern United States of America.

Offshore mariculture of shellfish has been undertaken on an experimental scale at a number of locations in temperate regions where large-scale commercial shellfish farming is more prevalent (Bonardelli and Levesque 1997; Chambers *et al.*, 2003; Langan 2000a; Langan, 2000b). These have concentrated on submerging traditional suspended longline and pearl net culture systems to depths of 20 m below the sea surface to avoid the difficulties of retaining surface floats in exposed open waters, but with stronger mooring systems. This approach has worked well and survived the effects of high winds (100 km/h) and seas generated by a hurricane, as well as wave heights in excess of 6 m (Langan, 2000a; Paul, 2000). However, some difficulties have been encountered in maintaining the correct depth as the growing mussels add increased weight to the submerged floats. As a result, floats may collapse owing the increased water pressure from being pulled to greater depths (Chambers *et al.*, 2003). Besides the failure of floats, other problems with fouling and predation have been reported (Chambers *et al.*, 2003; Hampson *et al.*, 1999).

In the North Sea, the Alfred Wegener Institute in Germany and its partners have explored the combination of offshore mariculture of shellfish and seaweeds and offshore windmills for energy production (Buck *et al*., 2006). The site selected, close to the lighthouse "Roter Sand" located offshore in the German Bight, southern North Sea, has strong tidal currents, waves that can reach 3–4 m in height and a current velocity of up to 2 m/s. There are also major offshore shellfish farming activities in the Yellow Sea and other regions of Southeast Asia. In some locations the shellfish longline and structures for farming macroalgae extend for more than four kilometres into offshore waters.

The majority of the global macroalgae production is undertaken in Asia, with China alone responsible for about two-thirds of the global production, some of which is produced in exposed waters (e.g. the integrated multitrophic mariculture of algae, bivalves and fish in the Yellow Sea). The farming technologies for the macroalgae are very similar to those used for shellfish, i.e. longline structures organized in such a way to ensure optimal supply of light and inorganic nutrients for the seaweeds. Because of the need for sunlight, the macroalgae farms tend to extend over large areas of surface waters and, thus, to some extent magnify the challenges of deploying mariculture equipment in the open sea. The requirement for light also means that submersion as a way of avoiding heavy seas is a much less suitable solution for macroalgae than it is for finfish and shellfish.

The amount of published information on offshore seaweed farming remains limited, and marine plant mariculture has generally not attracted a great deal of research or commercial attention in many developed countries (Buck and Buchholz, 2004). However, the current global interest in utilizing plant material for the production of renewable biofuels is drawing considerable attention to the potential for open-sea farming of fast growing macroalgae species in many parts of the world.

The offshore mariculture systems for shellfish and macroalgae are less complex than for fish and have mostly relied on adapting inshore farming systems to offshore conditions. This technology for offshore mariculture of shellfish and macroalgae is also more easily transferable to other locations and countries. However, the challenges for growing production from offshore mariculture of shellfish and macroalgae relate more to economic viability of the activity due to higher operating costs, and potentially lower productivity due to less availability of nutrients in many open sites.

Continuing innovation and development is enabling mariculture to move into more exposed waters farther from the coast and potentially opening up substantial new areas for mariculture production. While more development is needed before many of the emerging mariculture technologies are practical for commercial farming, there is a need to anticipate their eventual arrival and ensure that government regulators are prepared for the arrival of new technology.

4.2 Main operational challenges of offshore mariculture

Offshore mariculture engineering has made considerable progress over the last few decades; however, there is still a long way to go to advance offshore mariculture systems for finfish, shellfish and macroalgae into consistently commercially viable production systems. These systems need to include seeding, feeding, grading, harvesting, cleaning and monitoring of the farms, all of which have to be carried out in offshore environments often under difficult and dangerous conditions. Some economic modelling and initial commercial production systems strongly suggest that economic viability of commercial offshore fish farms can only be achieved if the installations are large enough with a production comparable with, or larger than, the largest existing off-the-coast fish farms currently in operation (i.e. >10 000 tonnes/year) and with even larger-scale installations for shellfish and macroalgae.

Feeding

Proper diet and daily feeding are critical to the efficient mariculture of healthy fish. Yet, in the open ocean, storms and high winds make regular feeding and observation of fish a substantial engineering and operational challenge. As a result, developing remotely operated systems for reliable feed delivery in an unpredictable environment has become a priority. Most feeding technologies currently employed in coastal and off-the-coast mariculture (e.g. salmon systems) may not be fully applicable in offshore conditions. Indeed, controlling remote feeding and monitoring of offshore farms from a nearby platform or an anchored barge may only be feasible for offshore locations where the weather is never too extreme. Common and well-tested feeding systems distribute feed pellets through individual floating pipes going from feed storage facilities (usually floating storage silos/barges) to individual cages. This technology will certainly need to be further developed if it is to be used in offshore mariculture operations, particularly in terms of designing a distribution system that can withstand sudden and prolonged adverse weather conditions.

Technical developments in this area are already under way with innovative feed storage, transportation and delivery prototypes that could be suitable for offshore aquaculture applications. For example, the University of New Hampshire in the United States of America has developed prototype systems for remotely operated feed buoys based on a cylindrical spar-shaped design that are suitable for exposed offshore waters. A structure of this kind, remotely controlled and potentially powered by solar or wave energy, will reduce both labour requirements and the frequency of trips offshore to deliver the feed, as well as allowing farms to be located farther away from the coast. These systems already allow land-based monitoring of the fish through underwater video, as well as the ability to check the position of the feed buoy and the control and monitoring of feeding operations.

Maintenance of mariculture systems

Maintenance of mariculture nets or line structures, and other labour-intensive activities, such as seeding, grading and harvesting, is much more difficult to undertake in an offshore setting than in protected waters. For example, in finfish mariculture, the stock sometimes needs to be corralled into a confined area of a sea cage so it can be harvested by lifting from the water or treated for disease in a more confined space. Corralling fish in sea cages is sometimes done by installing a fixed partition in the cage and rotating it at the surface so the fish are crowded into one segment. However, such simple techniques are more difficult or impossible in an offshore mariculture situation, such that alternative methods have to be developed for achieving the same end result.

Marine biofouling of structures and farm stock is a significant challenge for mariculture operations. For shellfish, mechanical cleaning on the deck of a boat is the most common cleaning method, sometimes combined with dipping in a fluid that kills some of the biofouling organisms. The method is basically identical for macroalgae. In finfish farming, the cleaning strategies include replacement of the fouled net with a clean one and washing of fouled nets onshore, air drying by lifting part of the net out of the water, or cleaning nets from the surface with specific equipments, and cleaning *in situ* by divers. These methods are often used in combination with coating, impregnating or constructing with net materials that deter fouling organisms. The physical removal of biofouling from offshore mariculture structures through scrubbing and scraping, high-pressure water blasting, and net changes will be problematic because of greater wind and wave conditions, and will therefore require the development of novel solutions. For example, the completely enclosed Aquapod (www.oceanfarmtech.com) enables the finfish cage to be rotated so that portions of the net are exposed to the air to help remove biofouling by drying out.

Research is in progress on new antifouling compounds and materials, some of which may have potential for application in offshore mariculture operations. These include: biological control (using natural grazers); new materials such as non-toxic antifouling coatings; electrical methods (e.g. generating biocides, pH shift); and new shellfish handling and immersion techniques (Chambers *et al*., 2006).

Monitoring and process control

Remote monitoring and control of mariculture operations, such as feeding fish, is rapidly becoming well established in coastal mariculture and off-the-coast mariculture. These remote systems have already become important in operating offshore mariculture systems and are ultimately likely to be a key part of their successful operation.

The monitoring and control systems of the production process may include:

- computer-supported management systems for individual cages of cultured fish;
- cameras for observation of fish feeding behaviour and health conditions that are positioned above, below and inside the cage;
- interactive system for planning, monitoring and controlling feeding;
- eco-sensors for the monitoring of feed losses;
- automated systems for removal of dead fish and the monitoring of growth and survival;
- integrated operational control systems that allow a wide range of remote operations.

The monitoring of the production environment may involve:

- temperature, salinity and oxygen sensors;
- water current velocity, wave conditions;
- light conditions.

The monitoring of the production system may involve:

- mechanical system integrity – condition of moorings;
- remotely operated vehicle (ROV) for net monitoring and undertaking maintenance tasks;

- predator exclusion mechanisms to safeguard the farms and the fish;
- surveillance for intruders or vandals;
- monitoring of fish health and growth using advanced computer vision and analyses systems.

The long-term goal for offshore mariculture should be to develop integrated farming systems that are mechanized and remotely controlled as much as possible. Above all, there must be emphasis on reducing the need for people and vessels to have to spend time travelling to offshore mariculture sites, and once there, working under difficult conditions at sea, especially if diving is involved. If offshore mariculture is to fulfil its promise and develop on a large scale, it must find ways to use people for oversight of mechanical and management systems rather than for physical performance of farm operations, which is the norm in most coastal mariculture.

Other mariculture operational issues

There are a number of operating aspects of offshore mariculture that will require the development of alternative methods than are currently used in coastal mariculture and off the coast mariculture. It is generally assumed that these challenges will be solved for actual species and for the specific mariculture technologies being developed for open waters. Some important operational aspects are: seeding and juvenile supply into offshore mariculture systems; harvesting and slaughtering; waste management; health and welfare; surveillance for predators, intruders and/or vandals; other aspects of biosecurity; and training of personnel for operation. Most of these challenges will be relevant for all types of farmed organisms, although the operational challenges for the mariculture of macroalgae is likely to be less demanding than for finfish.

Feeds for offshore mariculture

Shellfish and macroalgae extract the resources they need for growth from seawater, but all current candidate finfish species for offshore mariculture appear to be marine carnivores or omnivores, with a requirement for a dietary source of marine lipids, including highly unsaturated n-3 fatty acids (n-3 HUFA) and some fishmeal in their feeds (Tacon and Methian, 2008; Olsen, 2011). Recent developments have shown that the fishmeal component of fish feeds can be replaced to a large degree by proteins from agriculture plants (Tacon, Hasan and Metian, 2011). However, carnivorous fish species will continue to require a certain amount of n-3 HUFA in their diets. It is an ultimate long-term challenge for all types of mariculture to obtain new sources of n-3 HUFA for feed, and particularly DHA (22:6 n-3), an important component of a healthy human diet. Farmed macroalgae, cultured microalgae, other suitable single-cell biomass and transgenic oil crop plants that produce DHA and EPA are among the most likely new and renewable resources for these important lipids (Olsen, Holmer and Olsen, 2008; Duarte *et al*., 2009; Naylor *et al*., 2009; Nichols, Petrie and Singh, 2010; Olsen, 2011).

Animal production in both agriculture and aquaculture represent a pressure on available plant and animal resources that could otherwise be consumed directly by humans instead of being fed to the farmed animals. It could be suggested that with the increasing global population of humans over time, these plant and animal resources will be increasingly used for direct human consumption. However, the fish that are used for the production of fishmeal and fish oil are limited to the extent that they can be consumed directly by humans owing to their composition. However, aquaculture is currently the most efficient means for converting fishmeal and fish oil to acceptable forms of human food.

There appears to be potential for macroalgae to be grown and processed into major key ingredients for feeds for finfish so that mariculture can become self-sustaining with less interference with the current supply chain of food for humans (Duarte *et al*., 2009). Seaweed nutrients are protected by indigestible cell walls or chemically bound in a way that diminishes their potential nutritional value in the raw state. Indeed, processing or biorefining the raw plants to make the nutrients they contain more available may be the way to proceed to ensure progress in this challenging field.

4.3 Characteristics of the production environment and spatial potential for offshore mariculture

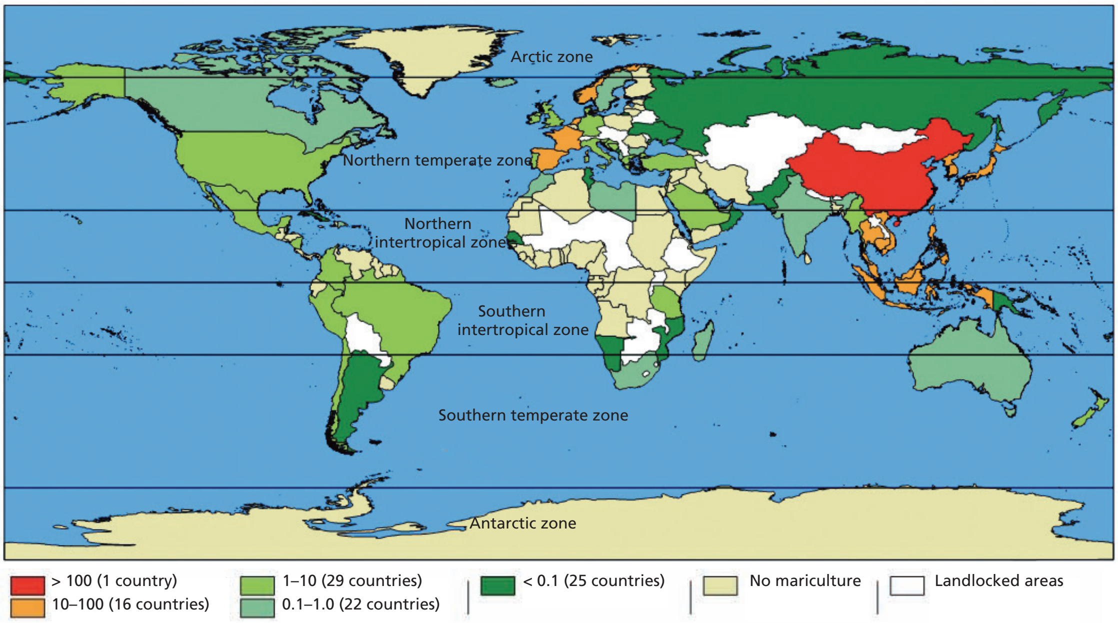
Kapetsky, Aguilar-Manjarrez and Jenness (2013) conducted a GIS-based global assessment of the status and potential for offshore mariculture development from a spatial perspective, tabulated in Appendix 1,[2] as inputs to the discussions of the current workshop and synthesis. The results of the assessment provide an indication of near-future global and national potential for the expansion of mariculture from present nearshore locations to offshore areas, and aim to stimulate much more comprehensive and detailed assessments of offshore mariculture potential at national levels. The part of the study on the present status of mariculture indicates large, unrealized offshore mariculture potential. Mariculture is widespread throughout all of the global climate zones except Antarctica. In all, 93 countries and territories practised mariculture during the period 2004–2008, but a further 72 (44 percent) were not yet practising mariculture. The intertropical zone and the northern temperate zone are the most developed global climate zones for mariculture. Several important mariculture nations span more than one climate zone, especially China, which is by far the world's leading producer. The intensity of mariculture production as measured in tonnes per kilometre of coastline is highly variable around the world, ranging from a fraction of a tonne in many countries up to 519 tonnes/km in China (Figure 7). About half of the mariculture nations have outputs of less than 1 tonne/km of coastline. Globally, the length of coastline available for mariculture is about 1.5 million km, with about 17 percent distributed among countries not yet practising mariculture. About one-half of inshore mariculture production consists of aquatic plants, but there is little production of plants offshore. Altogether, this evidence points to an apparent widespread underutilization of marine space for mariculture.

Another part of the study deals with offshore mariculture potential. The estimates for offshore potential are based on some key assumptions about the near-future development for offshore mariculture. Among these were that offshore mariculture will develop within economic exclusive zones (EEZs), will mainly use cages for finfish and longlines for mussels modified for offshore conditions, and will mainly employ species with already proven mariculture technologies and established markets. The assumptions set the stage for the establishment of analytical criteria and thresholds that are at the core of the spatial analyses. Thus, EEZs were used as spatial frameworks to define the limits of national offshore mariculture development.

The analytical criteria and corresponding thresholds used to define the technical limits on cages and longlines were depths (25–100 m) and current speeds (10–100 cm/s). Likewise, the criteria that defined the cost-effective area for development of offshore mariculture were cost limits on travel time and distance from shore to offshore installations (25 nm [46.3 km]) and reliable access to a port. This analysis showed that, relative to the entire EEZ area, near-future offshore mariculture is limited spatially by the need to tether cages and longlines to the seafloor (Figure 8). In this regard, the EEZ area is either currently too deep (88 percent) or too shallow (4 percent) for cages and longlines based on the depth thresholds of 25–100 m (Figure 9, upper pie chart).

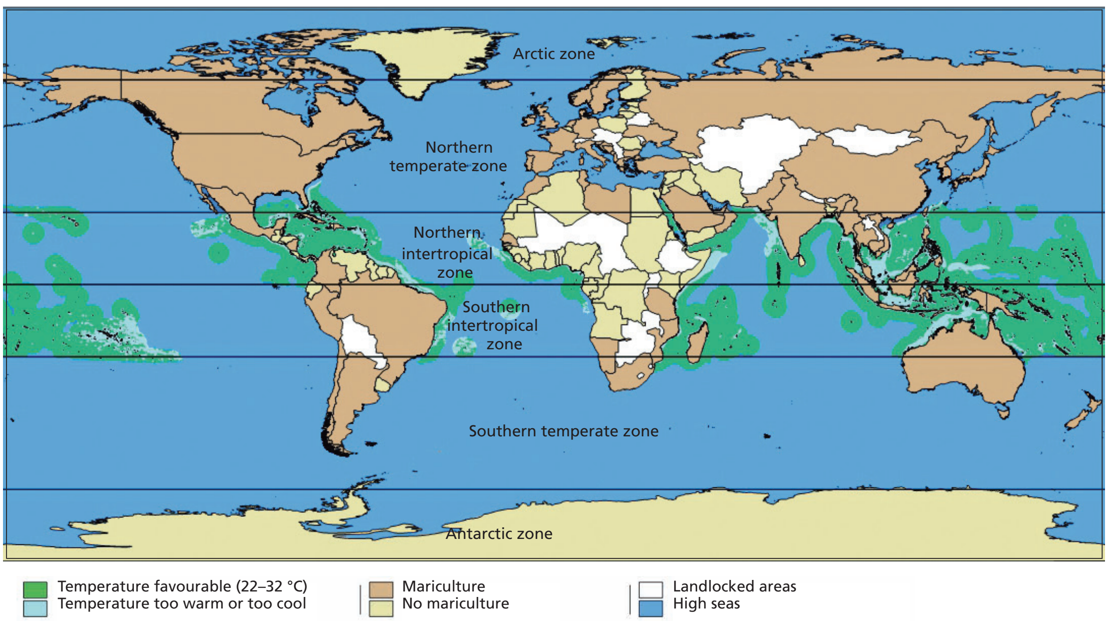
[2] Table A1 in Appendix 1 reports numbers of nations and aggregated areas meeting various criteria for the status and potential offshore mariculture.
Table A2 in Appendix 1 is a summary of status and potential of offshore mariculture by ranks of climate zones and by mariculture and non-mariculture nations (i.e. nations not yet practising mariculture).
Table A3 in Appendix 1 lists sovereign nations first in status and potential for offshore mariculture by surface area in each climate zone and by mariculture and non-mariculture nations.

FIGURE 7
Intensity of mariculture production from 2004–2008 in tonnes per kilometre of coastline and numbers of countries in the range



Source: Kapetsky, Aguilar-Manjarrez and Jenness (2013).

FIGURE 8
Areas within EEZs with temperatures favourable for offshore grow-out of cobia



Source: Kapetsky, Aguilar-Manjarrez and Jenness (2013).

Moreover, in about 7 percent of the EEZ area, either depth is within the 25–100 m threshold or current speed is within the 10–100 cm/s threshold, but these thresholds do not occur together (Figure 9, upper pie chart). Thus, only about 1.4 million km^2 (0.87 percent) of the EEZ area remain where both depth and current speed are suitable for cages and longlines (Figure 9, bottom pie chart).

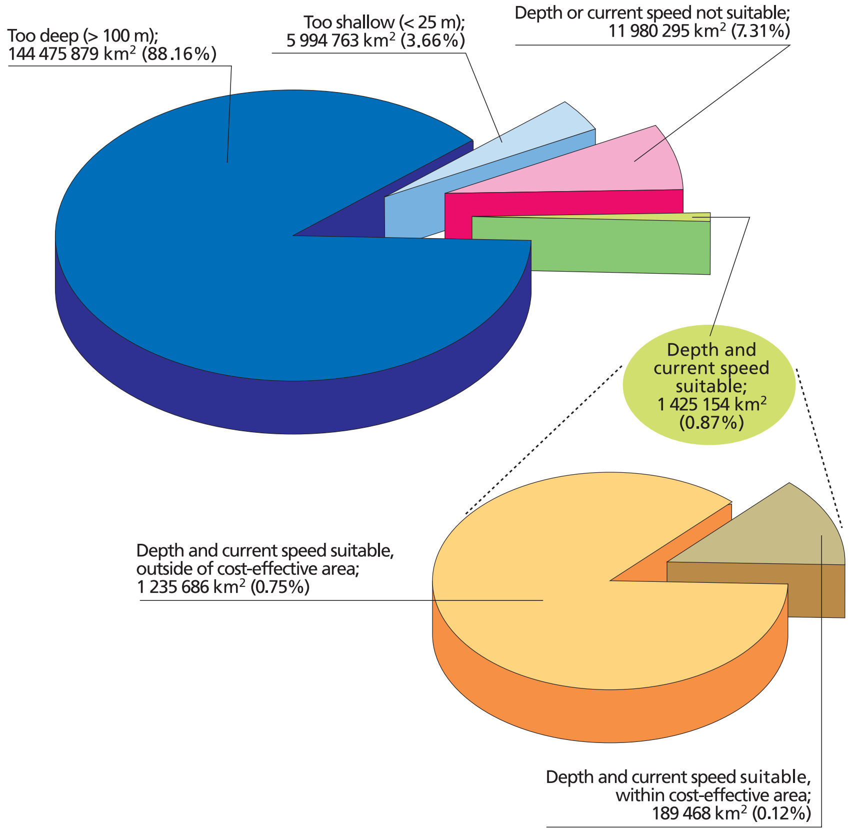
The physical and chemical characteristics of coastal seas and the open ocean are greatly influenced by latitude, continental shapes, major currents and ocean circulation. Seawater temperature and its spatial and temporal variability are critical for determining the species that are suitable for mariculture in offshore waters, but other factors (as indicated above) are also relevant. A major difference between tropical and temperate waters is the higher temperature and the smaller seasonal variability in the sea surface temperature in the tropics as illustrated by the vast areas within EEZs with temperatures favouring grow-out of cobia (22–32 ºC) (Figure 9).

The areas span the globe in much of the Intertropical Convergence Zone and in small portions of the Northern and Southern Temperate Zones.

The potential of cobia for offshore mariculture development as well as of two other species that meet the culture system technology and market requirement criteria, Atlantic salmon and blue mussel (*Mytilus edulis*), was further assessed by integrating the areas with favourable grow-out temperatures with depths and current speeds suitable for submerged cages along with the cost effective area for development. Favourable grow-out of fish and mussels was defined by water temperature (22–32 °C for cobia, 1.5–16 °C for Atlantic salmon, and 2.5–19 °C for blue mussel). In the case of blue mussel, favourable growout was also assessed by food availability measured as chlorophyll-*a* concentration (>0.5 mg/m^3). Potential for offshore integrated multitrophic aquaculture (IMTA) of the latter two species was also analysed.

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

FIGURE 9
Areas within EEZs relative to depths and current speeds suitable for sea cages and longlines and to the cost-effective area for development



Source: Kapetsky, Aguilar-Manjarrez and Jenness (2013).

TABLE 6
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[1] (tonnes/km²)	Total area suitable for development (km²)	5% developed		1% developed	
			Area (km²)	Production (tonnes)	Area (km²)	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**

[1] Nash (2004).

Source: Kapetsky, Aguilar-Manjarrez and Jenness (2013).

substantially increase overall mariculture production (Table 6). 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.

This global assessment provides 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 practising mariculture that have a high offshore potential. As FAO moves towards guiding the development of offshore mariculture through its regional fishery bodies and via technical assistance at national levels, more detailed assessments will need to be undertaken to determine the regions and countries that are most promising for development.

5. ENVIRONMENTAL INTERACTIONS OF OFFSHORE MARICULTURE

The most relevant environmental issues of offshore mariculture are those related to: (i) the biogenic waste and inorganic nutrients emission from fish farming affecting the water quality and the potential impacts on pelagic and bottom ecosystems (particularly sensitive habitats); (ii) escapees and genetic interactions with wild stocks; (iii) disease and use of chemical agents; and (iv) interaction with wild stocks and fisheries.

Existing data on the environmental effects of offshore mariculture are scarce and/or inadequate. The current state of knowledge must preliminarily be built based on the general knowledge and concepts resulting from existing and most relevant studies on mariculture (Holmer, 2013; Angel and Edelist, 2013). It is also important to have a fundamental understanding of the effective environmental risks of mariculture in open waters before properly adapted national regulations, international agreements and harmonized evaluation tools can be developed and/or proposed. The risk evaluation of offshore ABNJ mariculture should be made on a scale comparable with that already available for fisheries in international waters. There is already a general understanding in international law that activities that have a high risk of significant negative impact on marine ecosystems must be distinguished from those that most likely have minor impacts. It is therefore a challenge of science to suggest a robust, scientifically based management concept that clearly defines unacceptable impacts from those impacts that are minor and acceptable as a normal consequence of industrial activity.

It should be noted that other environmental interactions that may be important in coastal and nearshore mariculture operations may be of lesser concern in offshore farming activities, such as visual pollution, noxious odours and excessive noise interactions, owing mainly to the distance of the commercial activities.

5.1 Biogenic waste emission and inorganic nutrients

Pelagic ecosystems and water quality

There is in general a relatively poor understanding of how wastes from cage aquaculture systems disperse and affect the structure and function of the pelagic ecosystem (Cloern, 2001; Olsen *et al.*, 2006; Holmer, 2013; Angel and Edelist, 2013). Consequently, there is no clear scientific basis established for monitoring and managing environmental impacts for mariculture in open waters. It is primarily the inorganic nutrients such as ammonia and phosphate that may affect pelagic ecosystems, and the circumstances for protected and exposed mariculture sites is conceptually the same. The application of the precautionary approach principle has therefore been advocated because of the lack of scientific knowledge. However, it should be noted that a few assessment studies have identified serious impacts of mariculture activities on pelagic ecosystems (see Table 7).

According to the generic knowledge on nutrient point sources in marine waters, the following factors are important for offshore mariculture: (i) the size of the source, i.e. the specific release rate from the farm; (ii) the prevailing hydrodynamic forces, i.e. responsible for the dilution rate of the released nutrients and organic wastes; and (iii) the assimilation rate of nutrients and wastes into the natural food web.

Fish feeding is the primary driver of ecosystem impact as a result of biogenic wastes. Macroalgae and shellfish are not artificially fed, thus representing nutrient sinks, and hence are not further covered. The quantitative nutrient/waste emission from intensive aquaculture can be estimated by mass balance based on comprehensive statistical information on feed use and fish production combined with information on feed losses, contents of nitrogen (N) and phosphorus (P) in the feed and the fish, and assimilation efficiencies of the dominant N and P components of the feed (Olsen, Otterstad and Duarte, 2008; Olsen and Olsen, 2008; Reid *et al.*, 2009). For nutrients N and P, such estimates are particularly robust for N when feed losses are low, the natural feed supply to the aquaculture system is low, and the statistical information on production and use of feed is adequate for the purpose. The pelagic ecosystem is primarily exposed to the inorganic nutrient fraction. This approach is applicable to offshore mariculture as long as feed input, mortality and harvesting are carefully monitored.

Nutrient uptake and allocation in planktonic food webs and water hydrodynamics are the fundamental processes determining the assimilation capacity of the water column. Generally, if the dilution rate, mediated by the prevailing hydrodynamic conditions, ensures a dilution of the nutrient wastes to near natural concentrations before they affect phytoplankton and their grazers, negative environmental impacts are unlikely to occur, while the wastes may only stimulate natural production, which could possibly be regarded as a positive effect (Olsen *et al.*, 2007). Preliminary results obtained for typical off-the-coast salmon farms in central Norway have revealed that the ammonia uptake rate (biological assimilation) is much slower than the dilution rate at typical water current velocity rate of about 10 cm/s.

In general, there are no main differences, other than logistical ones, in assessing water column impacts of coastal and offshore mariculture farms. Moreover, this is valid across latitudes and weather conditions. The main assessment methods include dose estimation, waste dispersal (which can be simulated by 3D modelling) and impact evaluation based on dilution and biological assimilation rates. Other impact indicators suggested include enhanced ammonium (NH_4) concentration, growth responses in dialysis cultures and changes in the concentration of particulate nutrients (see Table 7).

Bottom ecosystems and sensitive habitats

In contrast to the poor understanding of the potential impacts on the water column, there is a relatively good scientific understanding on how particulate wastes, i.e. faeces and feed losses from mariculture, may disperse and ultimately accumulate in the sediments and benthic ecosystems below fish farms and in the immediate surrounding

TABLE 7
Overview of off-the-coast (OFC) and offshore (OFS) mariculture in different regions and its environmental impacts on water quality, sediment and benthic fauna

Species	Type	Location/region	Water quality	Sediment	Fauna (benthos)	Comment	Reference
Seabream/ seabass	OFS	East Mediterranean/ST	No impact	No data	No data	–	Basaran, Aksu & Egemen (2007)
Seabream	OFS	Canaries/ST	No data	Enhanced ON pools under cages	–	Low production	Dominguez *et al.* (2001)
Shellfish/ flounder	OFS	United States of America/T	No impact	No impact	No impact	Low production	Grizzle *et al.* (2003)
Atlantic tuna	OFC	West Mediterranean/ ST	No data	Enhanced OM pools and bacterial activity, reduced sediments	Disturbed community	–	Vezzulli *et al.* (2008)
Atlantic tuna	OFC	Adriatic/T	No impact	Enhanced P pools	No data	–	Matijevic, Kuspilic & Baric (2006)
Cobia	OFC	Puerto Rico/TR	No data	Enhanced ON pools under cages	No data	–	Rapp *et al.* (2007)
Salmon	OFC	Norway/B	No data	Increased sedimentation, increased P content	Increased production, abundance, biomass, reduction in diversity	230 m water depth - waste signals in bottom traps < 900 m away	Kutti, Ervik & Hansen (2007)
Salmon	OFC	Norway/B	No data	Reduced sediments <250 m, no change in OM pools except P	Increased production, abundance, biomass, reduction in diversity	230 m water depth	Kutti *et al.*, 2007; Kutti, Ervik & Hoisaeter (2008)
Seabream/ seabass	OFC	West Mediterranean/ ST	No impact	Enhanced OM pools under cages	Reduced species richness and abundance	Impact at 2 out of 5 farms	Maldonado *et al.* (2005)
Seabream/ meagre	OFC	West Mediterranean/ ST	No data	Enhanced OM pools under cages and downstream	Reduced species richness and abundance	–	Aguado-Gimenez *et al.* (2007)
Seabream/ seabass	OFC	Mediterranean/ST	No data	Enhanced P pools	Abundance shifts	Seagrass impacted	Apostolaki *et al.* (2007)
Seabream/ seabass	OFC	Mediterranean/ST	Nutrient availability enhanced up to 150 m	–	–	MedVeg project	Dalsgaard & Krause-Jensen (2006)
Seabream/ seabass	OFC	East Mediterranean/ ST	Transfer to higher trophic levels	No data	No data	–	Pitta *et al.* (2009)
Seabream/ seabass	OFC	Mediterranean/ST	–	–	Enhanced seagrass mortality	MedVeg project	Diaz-Almela *et al.* (2008)
Seabream/ seabass	OFC	Mediterranean/ST	–	Enhanced OM pools and bacterial activity, reduced sediments	–	MedVeg project	Holmer *et al.* (2007); Holmer & Frederiksen (2007)
Tuna	OFC	Mediterranean (Spain)/ST	No data	No change in OM pools	Disturbed community up to 220 m away	–	Vita *et al.* (2004)
Blue mussels	Coastal	Canada/B	No data	Enhanced OM pools and reduced sediments	–	–	Cranford, Hargrave & Doucette (2009)
Snapper/cobia	OFC	Puerto Rico/TR and Bahamas/ST	No impact	Enhanced ON pools under cages	–	Low production	Beltran-Rodriguez (2007); Benetti *et al.* (2006), (2008); Hincapié-Cardenas (2007)

TABLE 7 (CONTINUED)

Species	Type	Location/region	Water quality	Sediment	Fauna (benthos)	Comment	Reference
~40 species, cf footnote[1]:	OFC	China – 4 southern provinces/TR	No data (in English)	Enhanced OM , ON under cages in few reports	–	Large scale	Feng *et al.* (2005); Cao *et al.* (2007)
Pacific threadfin	OFS/TR	Oahu, Hawaii, United States of America/TR	No impact	OM enrichment	Disturbed faunal community up to 80 m from cages and altered microbial flora <300 m away	Low production	Helsley (2006); Lee, Bailey-Brock & McGurr (2006); Yoza *et al.* (2007)
Hawaiian yellowtail	OFC/TR	Big Is., Hawaii, United States of America/TR	No impact	No data	No data	>500 tonnes	N. Sims, personal communication, 2010
Cobia	OFC/TR	Viet Nam	No data	No data	No data	>500 tonnes	Merican *et al.* (2006)
Seabream/ seabass/red drum/siganids	OFC/TR	Mauritius	No data	No data	No data	Low production	Ministry of Agro-Industry and Fisheries of Mauritius (2007)
Red drum/ cobia	OFS/OFC	Réunion and Mayotte	No data	No data	No data	Low production	Dabaddie (2009)
Cobia	OFC	Belize	No data	No data	No data	Low production	Benetti *et al.* (2006), (2008)
Mostly cobia, also some tuna	OFC/OFS	Mexico, Brazil, Dominican Republic, Panama, Costa Rica, Ecuador	No data	No data	No data	Still low production or in different deployment phases	Stemler (2009); Benetti *et al.* (2008)
Barramundi	OFC	Australia	No data	No data	No data	Low prod	Rimmer (1995); Rimmer & Ponia (2007)
Barramundi	OFC	Papua New Guinea	No data	No data	No data	Low prod	Middleton (2004)
Sponge	OFS	Australia	No impact	No impact	No impact	Experimental	Duckworth & Wolfe (2007)
Seabream/ mullet	OFC	Oman	No data	No data	No data	Low production	Al-Yahyai (2009)
Red drum	OFC/TR	Martinique	No data	No data	No data	Low production	Dao (2003)

B: boreal; T: temperate; ST: subtropical; TR: tropical; ON: organic nitrogen; OM: organic matter; P: phosphorus

Note: "Low production" means <500 tonnes.

[1] Mostly cobia, amberjack, snapper, flounder, red drum and pompano; also seaweed and shellfish.

area (Tett, 2008). A quantification of the input is possible by using a mass balance method. It is also quite well understood how these accumulations of nutrient wastes distribute in sediments as a consequence of bottom topography, water current velocity, sediment structure and water depth (Cromey, Nickell and Black, 2002). Severe accumulations can cause major changes in the structure and function of benthic ecosystems locally, normally resulting in decreasing biodiversity and increased biomass of benthic heterotrophs (Pearson and Rosenberg, 1978; Soto and Norambuena, 2004). A consequence may be highly reduced conditions owing sulphide accumulation with a shift in decomposition of organic matter from fauna mediated to microbial processes, with inhibition of microbial processes such as nitrification and, secondly also denitrification (Holmer and Kristensen, 1992; Angel, Krost and Gordin, 1995). The result is high ammonium and phosphate release from sediments.

The following factors related to benthic impacts are considered important when moving mariculture to offshore sites: (i) the size of the particulate waste source, i.e. feed losses and particulate faeces; (ii) water depths and bottom topography; (iii) the specific hydrodynamic characteristics of a site (including surface and deeper water layers); (iv) the assimilation capacity of deep waters and benthic ecosystems; and (v) the presence of sensitive benthic habitats.

Feed losses can generally be reduced by using modern, camera and remote assisted feeding systems. Many of the commercially available systems can be used or adapted for offshore mariculture operations. The efficiency in the feed conversion ratio (FCR) is of paramount importance in both reducing the production costs and minimizing any environmental impact. In principle, feed losses can be almost totally eliminated in an optimal farming operation, and the only effective nutrient inputs to the environment would therefore be through the faeces and excretion, and these too could be minimized through optimizing feed composition and digestibility.

Water depths and water currents at the fish farm site and downstream will generally affect how widely sediments are distributed below and in the surrounding area of the farm. Bottom topography is also important, and locations over bottom ridges are presumably better than locations above the deepest holes in the seafloor. Depending on the depth and hydrodynamic characteristics of the farm site, filter-feeding organisms can remove some of the small particles before they reach the seafloor, but the majority of the larger particles, including uneaten feed pellets, will eventually reach the sediments. Enrichment of the benthic environment as a result of fast sinking particulate waste products from farms is considered to be one of the most significant impacts of mariculture (Hargrave, Holmer and Newcombe, 2008). Under exposed farming conditions, waste products can be dispersed over larger areas, but due to the fast sinking rates of feed pellets and faeces (Cromey, Nickell and Black, 2002; Magill, Thetmeyer and Cromey, 2006), the bulk of the sedimentation can generally be expected to occur in the immediate vicinity of the farms (i.e. within hundreds of metres).

The microbial processes will also respond to organic enrichment by enhancing their activity, and thereby increase the risk of hypoxia and reduced conditions in the sediments. Occurrence of hypoxia affects benthic fauna negatively, but areas where hypoxia occurs are frequently areas that are stagnant or with poor water exchange (Gray, Wu and Or, 2002). Thus, hydrodynamic factors are key processes determining whether or not hypoxia occurs. Offshore mariculture and off-the-coast locations should have less risk of hypoxia, although local hydrodynamic conditions and bathymetry have to be considered. Moreover, deep-dwelling benthic fauna, which are expected to be abundant in deep sediments, may suffer from hypoxia at higher oxygen concentrations, owing reduced conditions in the sediments (Hargrave, Holmer and Newcombe, 2008).

5.2 Sensitive benthic habitats

Moving aquaculture farther from the coast and to deeper waters will remove the pressure on coastal sensitive habitats, but there are probably other sensitive habitats at potential off-the-coast and offshore mariculture sites. Off-the-coast locations will probably include sensitive coastal habitats, especially in areas with clear water and deep light penetration, for example in the Mediterranean Sea, where seagrasses occur at 50–70 m water depths.

In general, there is a well-developed scientific background on benthic impacts from mariculture, including a number of impact proxies such as indicator species, diversity of species and groups, biomass of fauna, organic contents and biochemical measures, microbial status and aerobic conditions (Kalantzi and Karakassis, 2006; Brooks and Mahnken, 2003; Holmer, Wildish and Hargrave, 2005; Hyland *et al.*, 2005; Aguado-Gimenéz *et al.*, 2007; Hargrave, Holmer and Newcombe, 2008; Holmer, 2013; Angel and Edelist, 2013). There are various methods to measure these variables – established monitoring and management methods based on the scientific understanding of benthic impacts, including for example the MOM assessment method regularly used for large salmon farms (Hansen *et al*., 2001) and dynamic simulation models like DEPOMOD (Cromey, Nickell and Black, 2002).

Among the main challenges ahead is to increase the knowledge on the typical benthic habitats to be expected under offshore mariculture sites and to test and verify the applicability of existing environmental monitoring procedures used for coastal and off-the-coast mariculture.

5.3 Escapees and genetic interactions with wild stocks

Escapes from fish farms are mainly caused by external forces (e.g. strong winds, waves, predators and vandalism, and inappropriate or poor farm management practices). The prevention of escapes remains primarily an engineering and management challenge. Escaped farmed organisms are generally considered to be a major problem, but the perception of the potential impacts to the environment differs among countries, also depending on the farmed species. The diverse consequences may include: (i) the potential genetic interference with wild stocks (regarded to be particularly harmful if the cultured stocks are larger than the natural ones and if the cultured stocks are selectively bred); (ii) the potential transmission of parasites and diseases; and (iii) the competition for space by which escapees outcompete natural populations (particularly negative if native species are outcompeted by non-native species).

Atlantic salmon has undergone selective breeding for generations, and it has been estimated that cultured numbers exceed those of wild fish (Cross *et al.*, 2008). In this case, major escapes of farmed salmon mixing with wild populations may produce negative effects (McGinnity *et al.*, 2003; McGinnity *et al.*, 2004). However, at present none of the many finfish candidates for offshore farming (see Table 4) have undergone the same breeding programme as salmon, which, besides, may not be a very well-suited candidate for offshore mariculture.

The issue of potentially large escapes from offshore mariculture activities is continuously discussed among many stakeholders, mainly owing to the fact that future offshore operations will most likely be large and placed in areas generally under rough weather conditions. Escapes from shellfish and marine plant mariculture cannot be excluded, but so far this has apparently not been regarded as a specific environmental hazard, at least when local species are farmed. Being offshore can minimize the risks by being far away from potential reproduction or settling areas.

5.4 Disease and chemical agents

Pathogenic bacteria, viruses and harmful parasites can be both introduced and transmitted through mariculture activities, including through escaped fish. Pathogens and parasites normally originate from wild fish or invertebrate populations (Diamant and Paperna, 1995), but may reach epidemic proportions in intensively cultivated cages, as in the case of sea-lice and salmon (Goldburg and Naylor, 2004; Naylor and Burke, 2005). Pathogens abound in all environments, but owing to the greater natural biodiversity in the tropics, there is also a larger diversity of disease agents (Avise, Hubbell and Ayala, 2008). In addition, the rate of infection is magnified owing to the naturally high ambient temperatures, which affect metabolic rates of hosts and pathogens alike, and their activity levels.

Proper health management of livestock throughout its life cycle, adequate waste management, efficient vaccines, proper handling of pharmaceuticals, and effective treatments and maintenance of the water quality (particularly oxygen levels) are important to maintaining farmed fish healthy and preventing the spread of disease to other farms and wild fish. The spreading of pathogenic bacteria and viruses between farms is correlated with culture density, vicinity of farms and the local patterns of water currents. Relocation of farms to offshore mariculture sites can therefore be expected to reduce spreading of disease and parasites between farms, whereas an increase in the size of the farms may increase the risk of outbreak and disease at a single farm. The spread of disease to and from wild migrating fish stocks will depend on distances to major migration routes, to feeding and spawning grounds, as well as the level of attraction of the wild fish to the cages. Disease introduction and transfer can also be a concern in shellfish and seaweed culture systems (Boyd *et al.*, 2005).

A variety of chemicals are used in mariculture, including disinfectants, antifoulants and veterinary medicines (Costello *et al*., 2001; Read and Fernandes, 2003). Metals and other compounds may accumulate under cages (Dean, Shimmield and Black, 2007; Sutherland *et al*., 2007), in benthic organisms, and may be transferred through the food chain (Lojen *et al*., 2005). The impacts of antibiotics include effects on non-target organisms, effects on sediment chemistry and processes, and the ultimate development of antibiotic resistance (Beveridge, Phillips and Macintosh, 1997). The use of antifoulants may possibly increase in some offshore farming sites, whereas the use of medicines can be expected to decrease as a result of better environmental and culture conditions and larger distances between farms.

5.5 Interaction with wild stocks and fisheries

For offshore mariculture in the EEZ and ABNJ, it will be important to ensure that mariculture operations do not produce harmful interactions with wild migrating stocks. Mariculture farms may have considerable demographic effects on wild fish by aggregating large numbers in their immediate vicinity. Studies on seabream and seabass farms in the Mediterranean Sea have shown up to 30 different species of wild fish being attracted, with the aggregated biomass of wild fish at the majority of the investigated farm sites ranging between 10 and 40 tonnes (Dempster *et al.*, 2002, 2004, 2005). Similarly, large wild fish aggregations have been reported from fish farms in Greece (Thetmeyer, Pavlidis and Chromey, 2003) and the Canary Islands (Boyra *et al*., 2004; Tuya *et al*., 2006). Mussel rafts in the Mediterranean Sea (Brehmer *et al*., 2003) are also known to aggregate wild fish, whereas cold-water farms in the North Atlantic attract fewer species (Dempster *et al*., 2009). Large aggregates of saithe have been found around salmon farms showing a distinct morphology compared with natural fed species, with gadoid fish averaging over ten tonnes per salmon farm in Norway (Dempster *et al*., 2009). In the Mediterranean, the wild fish are dominated by a few primarily planktivorous fish feeding on feed pellets gone astray. Also demersal fish are attracted to fish farms, although aggregations vary in numbers and species. Increased levels of parasites and disease in wild fish (and disease transfer from wild to farmed fish) are potential impacts of the dense and temporally persistent aggregations present in close proximity to large biomasses of caged fish hosting parasites and diseases (Dempster *et al.*, 2002).

Offshore mariculture farms will presumably also attract large numbers of wild fishes, particularly as the farming operations are likely to be large, potentially increasing the availability of feed pellets lost in the immediate surroundings of the farm. This may be particularly the case in farms located close to the shore or near migratory routes and feeding and spawning grounds. A major concern of offshore mariculture farms is also the attraction of large predatory animals such as sharks and killer whales. On the Pacific coast of the United States of America and Canada, the Californian sea lion (*Zalophus californianus*), the harbour seal (*Phoca vitulina*) and the Steller sea lion (*Eumatopias jubatus*), interact with coastal fish farms by predating upon salmonids inside the cages and damaging netting in the process (Nash, Iwamoto and Mahnken, 2000). On the Atlantic coast, harbour seals and grey seals, *Halichoerus grypus*, cause similar problems (Nash, Iwamoto and Mahnken, 2000). In Chile, negative interactions of sea lions (*Otaria flavescens*) with salmon farms have been described (Sepulveda and Oliva, 2005). Sea-otters have also caused conflicts with production in specific regions.

Locating farms far away from marine mammal colonies is a good option and, thus, offshore aquaculture offers an opportunity to avoid interaction with them.

5.6 Integrated multi-trophic aquaculture

The ecological rationale of integrated multitrophic aquaculture (IMTA), which includes among others waste reclamation through trophic relationship and water quality maintenance through complementary functions of the farmed species, has recently attracted considerable interest from Western, as well as, other aquaculture nations (Chopin *et al*., 2001; Neori, 2008; Soto, 2009).

In the case of offshore mariculture, IMTA is being conducted by farming commercially valuable bivalves and macroalgae using longline systems installed in the vicinity of fish farms for these secondary crop species to take advantage of the wastes generated from the finfish. It has been demonstrated that bivalves close to the fish cages readily consume drifting faecal and feed particles; while in more distant locations, they will filter phytoplankton cells produced from inorganic nutrients released from the farm. The macroalgae may take advantage of the inorganic nutrients released, often a major waste from fish farms. The main driver of IMTA is the artificial feeding of finfish. Integrated multitrophic aquaculture farming may add value to the overall farming investment through the production of secondary crops, while at the same time mitigate any environmental impact through the reduction of waste dispersed. In other words, there is both an economic and an environmental drive for establishing IMTA operations.

In principle, IMTA in the sea is an environmentally friendly way of developing mariculture; however, an important question remains on the overall risks and achievable economic gains which may be very site-specific. In offshore mariculture locations, it is likely that food particles and nutrients disperse rapidly as a result of the hydrodynamic characteristic of the sea. Nevertheless, the rapid nutrient uptake capabilities of macroalgae may suggest that culturing macroalgae provide an additional economic incentive to go for such integrated development. IMTA driven by finfish cage culture may need to be further explored, considering that the growth of shellfish and macroalgae will also depend on the natural resources available in the ambient waters. The natural biological richness of the system or the capacity of the feed system to provide enough food for the extractive species is therefore fundamental for determining the economic potential of IMTA.

5.7 Minimizing environmental impacts

A risk assessment and environmental impact assessment and monitoring must always be in place before establishing offshore farms. FAO provides guidance that can be applied to the environmental concerns of offshore mariculture through different publications and guidelines including on health management for responsible movement of live aquatic animals (FAO, 2007), guidelines on the genetic resources management in aquaculture (FAO, 2008b), and on the ecosystem approach to aquaculture (FAO, 2010). Other relevant technical publications include global environmental assessment and monitoring of aquaculture (FAO, 2009) and understanding risk assessment and risk management in aquaculture (Bondad-Reantaso, Arthur and Subasinghe, 2008).

6. A VISION FOR THE FUTURE GLOBAL MARICULTURE INDUSTRY

Some relevant premises were agreed by the workshop participants: (i) there is a strong need for more seafood in the future; (ii) this seafood will partly need to come from mariculture in more exposed sites; (iii) there is a need to increase the harvest of marine organisms (wild and farmed) from lower trophic levels to minimize ecosystems impacts and ensure long-term sustainability while balancing these efforts with the global food and nutrition needs; and (iv) market forces alone cannot secure a balanced sustainable development. With such premises in mind, it is paramount to establish a clear vision for the future use of the global oceans for food production.

The overall vision for global mariculture in the twenty-first century is a "self-sustaining mariculture of quality and affordable seafood in harmony with the environment and its stakeholders". More specifically, some of the elements of the above vision would include:

- The twenty-first century will involve a "blue evolution" resulting in a rapidly increasing proportion of overall meat for human food being produced through coastal, off-the-coast and offshore mariculture.
- The feed resources for finfish will increasingly be derived from macroalgae and/or from other sources that are not taken from the human food chain, and thus the production trend will become more ecologically efficient and sustainable.
- Feed conversion rates are low, feed losses are minimized and escapes strongly reduced in all mariculture production.
- Mariculture production is undertaken in suitable areas where environmental impacts and stakeholder interactions and conflicts are minimized; the expansion of mariculture away from the ultimate shoreline to offshore locations becomes an important strategy to achieve this goal.
- An efficient national and international legal framework for mariculture is established.

The vision offers the following main political, scientific and industrial long-term challenges:

- There must be a strong political appreciation among key countries and international organizations on the importance of developing a robust and sustainable global mariculture industry that has the framework and capacity to facilitate the more rapid expansion of production in exposed open waters.
- Spatial planning with an ecosystem approach will need to be undertaken to identify the regions and countries that are most promising for offshore mariculture development, and to determine carrying capacities for maximum production and preservation of ecosystem services, including social carrying capacity.
- Suitable species must be identified and developed for offshore mariculture, because no particular finfish species that are currently in high production appear to be a clear candidate, and because most molluscs and macroalgae are currently not economically feasible for such production.
- Production systems, technology and operational procedures must be developed or improved, not through a revolution, but rather through an evolution, to allow production to be expanded to off-the-coast and offshore mariculture locations.
- New and more sustainable feed resources for fed-fish mariculture must be developed through long-term R&D efforts, and macroalgae have the potential to be an important raw material for feed ingredients.

- While feed pellets appear to be the most appropriate and environmentally friendly feed for off-the-coast and offshore mariculture aquaculture, the industry must install and apply modern feeding systems to minimize losses and secure feed conversion ratios well below 1.5 (dry feed supplied per wet weight produced).
- Science and industry must explore environmental impacts for off-the-coast and offshore mariculture and establish general principles for locating and monitoring this activity that are environmentally acceptable.
- Opportunities for minimizing environmental impacts while maximizing gains should be taken advantage of, such as the co-location of mariculture with offshore wind farms and oil and gas infrastructure.
- International collaboration and communication in developing offshore mariculture technology, best operational practice and regulatory frameworks will be critical for ensuring the rapid development of a sustainable global offshore mariculture industry.

The challenges of the vision are comprehensive, for science, society and industry, but no other issue is more important than to feed the world's populations in developing and developed countries in the twenty-first century. It is important for the global aquaculture industry to have a long-term roadmap towards its sustainability.

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Appendix 1

ESTIMATES OF STATUS AND POTENTIAL FOR OFFSHORE MARICULTURE

The status and potential for offshore mariculture was estimated by Kapetsky, Aguilar-Manjarrez and Jenness (2013) on the basis of surface areas and numbers of nations that meet various criteria. The technical criteria include water depths (25–100 m) and current speeds (10–100 cm/s) suitable for sea cages and longlines. The economic criterion is the cost-effective area for development, that is the area within 25 nm of a servicing port. Temperature identifies areas favourable for the growout of cobia (22–32 °C), Atlantic salmon (1.5–16 °C) and blue mussel (2.5–18 °C). For the latter, favourable growout is also defined by chlorophyll-*a* concentration (>0.5 mg/m^3).

The status and potential of offshore mariculture development are tabulated in three ways:

1. by numbers of nations and aggregate surface areas meeting various criteria (Table A1);
2. by ranks[1] of climate zones (Table A2);
3. by first ranked nations in each climate zone (Table A3).

In the tabulations, a distinction is made between nations in which mariculture is already developed or "mariculture nations" and those not yet practising mariculture or "non-mariculture nations". For reasons of economy of space many of the results presented in the tables are not discussed in the text of this Appendix; however, the results often relate to the text in other sections of this global synthesis or to the review papers that support this synthesis. For example, defining offshore mariculture is one of the topics of the synthesis, and depth is one of ways that mariculture zones can be defined. In this regard, Table A1 under the topic "Zones and Maritime Claims" provides the areas corresponding to the various depth zones. Four of the review papers in these proceedings deal with various aspects of offshore mariculture by climate zones. In this regard, Table A2 ranks offshore mariculture potential by climate zone based on the surface area meeting criteria and combinations of criteria. In the same vein, Table A3 identifies the first-ranked nation meeting the criteria and combinations of criteria in each climate zone based on the amount of surface area with potential.

Mariculture countries for the purposes of this study are those listed in the FAO aquaculture production statistics as having mariculture production originating from the marine environment in one or more years.

[1] A rank classification for suitability was set from 1–5 (i.e. 1 least suitable, and 5 most suitable) based on the amount of surface area meeting criteria.

TABLE A1

Summary of the status and potential for offshore mariculture development by numbers of nations and aggregate area meeting criteria

Present status of mariculture production

	Mariculture nations		Non-mariculture nations		Total	
Production	Nations and territories	Mean production (tonnes) 2004–2008	Nations and territories	Production (tonnes) 2004–2008	NA	NA
	93	29 976 736	72	0		

Present status of mariculture intensity

Mariculture intensity	Nations and territories	Production (tonnes/km coastline)
	93	–
Mean	–	15
Median	–	1
Maximum	–	520

Present status of mariculture coastline length

Coastline length	Mariculture nations		Non-mariculture nations		Total	
	km		km		Nations	km
	80	1 472 111	83	302 548	163	1 774 659

Notes:

Non-mariculture nations are maritime nations not yet practicing mariculture.

The results by Kapetsky, Aguilar-Manjarrez and Jenness (2013) are not discussed in Annex 1, but presented herein as relevant to Annex 1 and various review papers in these proceedings. For additional details and in depth analysis see Kapetsky, J.M., Aguilar-Manjarrez, J. & Jenness, J. 2013. *A global assessment of offshore mariculture potential from a spatial perspective*. FAO Fisheries and Aquaculture Technical Paper No. 549. Rome, FAO.

The differences in the number of nations and territories between mariculture production and intensity versus coastline length are attributed to the fact that two different spatial data sets were used (i.e. the number of countries/territories varied between these data sets). 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.

Zones and maritime claims

	Mariculture nations		Non-mariculture nations		Total	
	EEZs	Area (km^2)	EEZs	Area (km^2)	EEZs	Area (km^2)
Area of Exclusive Economic Zones	189	131 361 870	77	32 627 206	266	163 989 076

Zones and Maritime claims	Nations	Area (km^2)	Nations	Area (km^2)	Nations	Area (km^2)
Territorial Sea		20 750 899		4 587 804		25 338 704
Contiguous Zone		4 969 506		724 344		5 693 850
Economic Zone		118 730 541		23 774 037		142 504 578
Fishing Zone		12 404 048		69 008		12 473 056
Total	78	156 854 994	79	29 155 194	158	186 010 188

Mariculture zones defined by depth	Nations	Area (km^2)	Nations	Area (km^2)	Nations	Area (km^2)
1–10 m		2 010 632		260 325		2 270 956
Off the coast (10–50 m)		11 163 661		789 506		11 953 167
Offshore (50–150 m)		8 552 668		808 162		9 360 829
>150 m		109 597 945		30 405 078		140 003 023
Total	83	131 324 906	67	32 263 070	158	163 587 976

Technical feasibility for cages and longlines and cost-effective area for development (area 25 nm from a servicing port)

Technical feasibility and cost-effective area for development	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 for development	79	5 119 018	74	1 015 430	153	6 134 448
Cost-effective area for development and depths and current speeds suitable for cages	69	146 820	52	42 648	121	189 468

Note:
The varying numbers of nations reflect the fact that differing numbers of nations meet the various depths, current speed, cost-effective distance and other thresholds of the Kapetsky, Aguilar-Manjarrez and Jenness (2013) study. What is important here is the absolute number of nations that meet various criteria, not the relative numbers.

Environments favourable for growout integrated with technical criteria and the cost-effective area for development

Temperatures and chlorophyll-a concentrations suitable for favourable growout; depths (25–100 m) and current speeds (10–100 cm/s) suitable for cages and longlines

	Mariculture nations		Non-mariculture nations		Total	
	Nations	Area (km²)	Nations	Area (km²)	Nations	Area (km²)
Cobia temperature range 22–32 ºC	44	658 031	40	135 907	84	793 938
Atlantic salmon temperature range 1.5–16 ºC;	14	30 566	0	0	14	30 566
Chlorophyll-a >0.5 mg/m³	95	6 2376 545	54	717 804	149	6 994 349
Blue mussel temperature 2.5–19 ºC and chlorophyll-a >0.5 mg/m³	15	29 960	0	0	15	29 960
IMTA temperature 2.5–16 ºC and chlorophyll-a >0.5 mg/m³	9	14 590	0	0	9	14 590

Cost-effective area for development (area 25 nm from a servicing port), temperatures suitable for favourable growout, depths (25–100 m) and current speeds (10–100 cm/s) suitable for cages and longlines

	Mariculture nations		Non-mariculture nations		Total	
	Nations	Area (km²)	Nations	Area (km²)	Nations	Area (km²)
Cobia temperature range 22–32 ºC	42	66 188	38	31 004	80	97 192
Atlantic salmon temperature range 1.5–16 ºC	6	2 447	0	0	6	2 447
Blue mussel temperature 2.5–19 ºC and chlorophyll-a >0.5 mg/m³	11	5 848	0	0	11	5 848
IMTA temperature 2.5–16 ºC and chlorophyll-a >0.5 mg/m³	6	1 202	0	0	6	1 202

Locations that minimize competing and conflicting uses while taking advantage of possible complementary uses of marine space as illustrated by marine protected areas

	Mariculture nations		Non-mariculture nations		Total	
	Nations	Area (km^2)	Nations	Area (km^2)	Nations	Area (km^2)
Marine protected areas (MPAs) worldwide	93	3 533 612	51	296 957	120	3 830 569
Suitable inside MPAs for cobia offshore mariculture (temperature suitable; depths and current speeds suitable)	31	44 863	12	2 092	43	46 955

TABLE A2
Summary of potential for offshore mariculture by rank (from 1 to 5) of climate zones and by mariculture and non-mariculture nations based on aggregated surface area meeting criteria in each climate zone

Ranking: 1 least potential, to 5 highest potential

Criteria	Arctic	Northern temperate	Intertropical	Southern temperate	Antarctic
Present status of mariculture					
Production					
Mariculture [(1)]	3	2	1	4	0
Coastline length					
Mariculture	3	1	2	4	0
Non-mariculture	3	2	1	5	4
Mariculture intensity					
Mariculture	3	1	2	4	0
Zones and maritime claims					
Area of Exclusive Economic Zones					
Mariculture	4	2	1	3	0
Non-mariculture [(2)]	0	4	1	3	2
Maritime claims Territorial Sea + Contiguous Zone					
Mariculture [(3)]	3	2	1	4	5
Non-mariculture	0	2	1	5	4
Mariculture zones defined by depth Off the coast (10–50 m) + Offshore (50–150 m)					
Mariculture	3	1	2	4	0
Non-mariculture	0	2	1	4	3
Technical feasibility and cost-effective area for development					
Depths for cages and longlines (25–100 m)					
Mariculture	3	2	1	4	0
Non-mariculture	0	2	1	4	3
Current speed for cages and longlines (10–100 cm/s)					
Mariculture	4	3	1	2	0
Non-mariculture	0	4	1	2	3
Depths and current speeds suitable for cages and longlines					
Mariculture	4	2	1	3	0
Non-mariculture	0	2	1	3	4
Cost-effective areas (area 25 nm from a port)					
Mariculture	4	1	2	3	0
Non-mariculture	0	2	1	3	0
Cost-effective areas (area 25 nm from a port and depths and current speeds suitable for cages)					
Mariculture	4	2	1	3	0
Non-mariculture	0	2	1	3	0

TABLE A2 – CONTINUED

Environments favourable for growout: temperature and chlorophyll-a concentration suitable, depths (25–100 m) and current speeds (10–100 cm/s) suitable for cages and longlines	**Arctic**	**Northern temperate**	**Intertropical**	**Southern temperate**	**Antarctic**
Cobia temperature range suitable (22–32 °C)					
Mariculture	0	2	1	3	0
Non-mariculture	0	2	1	0	0
Atlantic salmon temperature range suitable (1.5–16 °C)					
Mariculture	3	2	0	1	0
Non-mariculture (4)	0	0	0	0	0
Blue mussel temperature and chlorophyll-a suitable (2.5–19 °C ; >0.5 mg/m^3)					
Mariculture	3	2	0	1	0
Non-mariculture	0	1	0	0	0
IMTA temperature and chlorophyll-a suitable (2.5–16 °C ; >0.5 mg/m^3)					
Mariculture	3	2	0	1	0
Non-mariculture	0	1	0	0	0

Environments favourable for growout and within the cost-effective area for development: temperature and chlorophyll-a concentration suitable, depths (25–100 m) and current speeds (10–100 cm/s) suitable for cages and longlines	**Arctic**	**Northern temperate**	**Intertropical**	**Southern temperate**	**Antarctic**
Cobia temperature range suitable (22–32 °C)					
Mariculture	0	2	1	3	0
Non-mariculture	0	0	1	0	0
Atlantic salmon temperature range suitable (1.5–16 °C)					
Mariculture	3	1	0	2	0
Non-mariculture	0	0	0	0	0
Blue mussel temperature and chlorophyll-a suitable (2.5–19 °C ; >0.5 mg/m^3)					
Mariculture	3	1	0	2	0
Non-mariculture	0	0	0	0	0
IMTA temperature and chlorophyll-a suitable (2.5–16 °C ; >0.5 mg/m^3)					
Mariculture	3	1	0	2	0
Non-mariculture	0	0	0	0	0

Locations that minimize competing and conflicting uses while taking advantage of possible complementary uses of marine space as illustrated by marine protected areas	**Arctic**	**Northern temperate**	**Intertropical**	**Southern temperate**	**Antarctic**
Marine protected areas (MPAs)					
Mariculture	3	1	2	4	5
Non-mariculture	0	3	1	2	4
Cobia suitable for temperature; cage and current speeds suitable inside MPAs					
Mariculture	0	2	1	3	0
Non-mariculture	0	2	1	0	0

Notes:
(1) There is no mariculture in the Antarctic Zone; (2) There are no non-mariculture nations in the Arctic Zone; (3) Some mariculture countries have territorial claims in the Antarctic Zone; (4) No ports are listed for the Antarctic Zone in the World Port Index (National Geospatial-intelligence Agency, 2009).

TABLE A3

Sovereign nations ranked first in surface area for offshore mariculture potential in each climate zone by mariculture and non-mariculture nations

	Mariculture nations					Non-mariculture nations				
	AZ	NTZ	ITZ	STZ	AaZ	AZ	NTZ	ITZ	STZ	AaZ
Present status of mariculture										
Production	Canada	China	China	Chile	–	–	–	–	–	–
Coastline length	Canada	Canada	Indonesia	Chile	–	–	Denmark [(1)]	Bangladesh	Antarctica	–
Mariculture intensity	Norway	China	China	Chile	–	–	–	–	–	–
Zones and maritime claims										
Area of Exclusive Economic Zones	Russia	United States of America	France	France	–	–	Egypt	Micronesia (Federated States of)	Antartica [(2)]	–
Maritime claims	–	–	–	–	–	–	–	–	–	–
Territorial Sea + Contiguous Zone	Canada	Canada	Indonesia	Australia	United Kingdom	–	Iran (Islamic Republic of)	Ecuador	Uruguay	–
Mariculture zones defined by depth	–	–	–	–	–	–	–	–	–	–
Off the coast (10–50 m) + Offshore (50–150 m)	Russia	United States of America	Indonesia	Argentina	–	–	Iran (Islamic Republic of)	Venezuela (Bolivarian Republic of)	Antarctica [(3)]	–
Technical feasibility and cost-effective area for development										
Depths for cages and longlines (25–100 m)	Canada	United States of America	Indonesia	Argentina	–	–	Iran (Islamic Republic of)	Venezuela (Bolivarian Republic of)	Antarctica	–
Current speed for cages and longlines (10–100 cm/s)	Denmark	United States of America	France	France	–	–	Egypt	Micronesia (Federated States of)	Antarctica	–
Depths and current speeds suitable for cages and longlines (25–100 m; 10–100 cm/s)	United States of America	United States of America	Indonesia	Australia	–	–	Egypt	Venezuela (Bolivarian Republic of)	Uruguay	–
Cost-effective area for development (area 25 nm from a port)	Norway	United States of America	Indonesia	Australia	–	–	Finland	Nigeria	Antarctica	–
Cost-effective area for development (area 25 nm from a port with depths and current speeds suitable for cages (25–100 m; 10–100 cm/s)	United States of America	Taiwan Province of China	India	Australia	–	–	Finland	Nigeria	Uruguay	–

Notes:

(1) Denmark figures prominently in the NTZ due to its association with Greenland; (2) Territorial claims in Antarctica are not identified in the Flanders Maritime Institute spatial database; (3) The Global Maritime Database identifies claims in Antarctica.

Terminology: AZ = Arctic Zone; NTZ = Northern Temperate Zone; ITZ = Intertropical Zone; STZ = Southern Temperate Zone; AaZ = Antarctic Zone.

TABLE A3 – CONTINUED
Sovereign nations ranked first for offshore mariculture potential by surface area in each climate zone and by mariculture and non mariculture nations

	Mariculture					No mariculture				
	AZ	NTZ	ITZ	STZ	AaZ	AZ	NTZ	ITZ	STZ	AaZ
Present status of mariculture										
Environments favourable for growout: temperature and chlorophyll-a concentration suitable, depths (25–100 m) and current speeds (10–100 cm/s) suitable for cages and longlines										
Cobia temperature range 22–32 °C	–	United States of America	Indonesia	Madagascar	–	–	Egypt	Venezuela (Bolivarian Republic of)	–	–
Atlantic salmon temperature range 1.5–16 °C	Norway	United States of America	–	Chile	–	–	–	–	–	–
Blue mussel temperature 2.5–19 °C and chlorophyll-a >0.5 mg/m^3	Norway	Denmark	–	Argentina	–	–	Poland	–	–	–
IMTA temperature 2.5–16 °C and chlorophyll-a >0.5 mg/m^3	Norway	United States of America	–	Argentina	–	–	–	–	–	–
Environments favourable for growout and within the cost-effective area for development: temperature and chlorophyll-a concentration suitable, depths (25–100 m) and current speeds (10–100 cm/s) suitable for cages and longlines										
Cobia temperature range 22–32 °C	–	United States of America	India	Madagascar	–	–	–	Nigeria	–	–
Atlantic salmon temperature range 1.5–16 °C	Norway	United States of America	–	New Zealand	–	–	–	–	–	–
Blue mussel temperature 4–18 °C and chlorophyll-a >1mg/m^3	Norway	Denmark	–	New Zealand	–	–	–	–	–	–
IMTA temperature 2.5–16 °C and chlorophyll-a >0.5 mg/m^3	Norway	United States of America	–	New Zealand	–	–	–	–	–	–
Locations that minimize competing and conflicting uses while taking advantage of possible complementary uses										
Marine protected areas (MPAs)	Denmark	United States of America	Kiribati	Australia	–	–	–	Ecuador	–	–
Cobia suitable for temperature, cage depth and current speeds suitable inside MPAs	–	United States of America	Australia	South Africa	–	–	Egypt	Micronesia (Federated States of)	–	–

Notes:
(1) Denmark figures prominently in the NTZ due to its association with Greenland; (2) Territorial claims in Antarctica are not identified in the Flanders Maritime Institute spatial database; (3) The Global Maritime Database identifies claims in Antarctica.

Terminology: AZ = Arctic Zone; NTZ = Northern Temperate Zone; ITZ = Intertropical Zone; STZ = Southern Temperate Zone; AaZ = Antarctic Zone.

Annex 2 – Workshop agenda

AGENDA AND TIMETABLE

	Monday, 22 March		
14:00–16:00	Welcome note, introductions and adoption of agenda		
	Initiative objectives and goals		
	Technical review – temperate – **J. Forster**		
	Technical review – tropical – **A. Jeffs**		
	Environment review – temperate – **M. Holmer**		
16:00–16:30	***Coffee break***		
16:30–18:00	Environment review – tropical – **D. Angel**		
	GIS spatial analysis – **J. Kapetsky**		
	Remote sensing – **J. Aguilar-Manjarrez**		
	Tuesday, 23 March		
08:30–10:30	Economic & marketing review – **G. Knapp**		
	Case Study I – Kona Blue – **N. Sims**		
	Case Study II – Salmon farming in Chile – **A. Alvial**		
	Policy and Governance review – **D. Percy**		
10:30–11:00	***Coffee break***		
11:00–12:30	Preliminary issues and actions identified for possible inclusion in the FAO global offshore mariculture development initiative – **Y. Olsen**		
	Formation of Working Groups and review of TORs		
12:30–14:00	***Lunch break***		
14:00–16:00	Working Group I	–	Technical issues
			Economic and marketing issues
	Working Group II	–	Environmental issues
			Policy and governance issues
16:00–16:30	***Coffee break***		
16:30–18:00	Working Group I	–	Cont’d
	Working Group II	–	Cont’d

	Wednesday, 24 March
08:30–10:00	Working Group I – Cont'd Working Group II – Cont'd
10:00–10:30	***Coffee break***
10:30–12:30	Working Group I – Cont'd Working Group II – Cont'd
12:30–14:00	***Lunch break***
14:00-15:30	Presentation of main conclusions and recommendations from the Working Groups and follow-up discussion – **Chairpersons / Participants** Working Group I
15:30–16:00	***Coffee break***
16:00–17:00	Working Group II
	Thursday, 25 March
09:30–10:30	Feedback and presentation of the draft FAO global offshore mariculture development initiative – **Y. Olsen / FAO**
10:30–11:00	***Coffee break***
11:00–12:30	Workshop follow-up actions Closing remarks
12:30–14:00	***Lunch break***
15:00	Departure for Rome

Annex 3 – List of participants

EXPERTS

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Annex 4 – Profiles of experts

EXPERTS

Adolfo ALVIAL – General Director of Adolfo Alvial Asesorías S.A., a consultancy company based in Chile providing support to the aquaculture sector, with emphasis in salmon farming. He is also President of the Business Incubator company INER Los Lagos, Member of the Directory Board of the Regional Agency for economic development, member of the Technical Council of the Technological Institute of Salmon of the Chilean Salmon Farming Association (SalmonChile), member of the Global Aquaculture Alliance Salmon Technical Committee. He has been Director of Marine Harvest – Chile Area, Director of the Technological Institute of Salmon, Director of the Aquaculture Division of Fundación Chile, Secretary General of the Arturo Prat University (former university of Chile – Iquique), and Director of the Marine Science Department at the same university. He has undertaken several research projects related to phytoplankton ecology in northern and central Chile, and on El Niño impacts on pelagic fisheries and aquaculture. He has been in charge of new aquaculture business developments in Chile, such as turbot, abalone, hirame, halibut, Chilean sole, hake and white sturgeon. He has published numerous papers in national and international science journals. Furthermore, Mr Alvial has produced a number of reports for private clients, including national and foreign governments, mostly on aquaculture, but also on environmental management and ecotourism. Adolfo Alvial has supported several aquaculture pioneer companies in Chile in salmon, abalone, and turbot production. His areas of expertise also include coastal zone management, integrated management systems in aquaculture and environmental monitoring and forecast systems in coastal waters.

Dror ANGEL – Senior researcher at the Recanati Institute for Maritime Studies and lecturer at the Departments of Marine Biology and of Maritime Civilizations at the Charney School of Marine Sciences, University of Haifa, Israel. He is also the head of the new International MA Programme in Maritime Civilizations at the same university. Dror, a Ph.D. in Biological Oceanography from the City University of New York, has been working in the field of aquaculture and marine ecology for the past 20 years. In addition to studying the interactions of aquaculture with the environment, Dr Angel has examined a number of different options, including artificial reefs and integrated aquaculture to ameliorate aquaculture effects, and to make the activity more environmentally acceptable and economically sustainable. In recent years, he has been involved in numerous efforts by FAO and the International Union for Conservation of Nature (IUCN) to apply the ecosystem approach to aquaculture and to establish applicable guidelines for the industry. Although he is primarily an ecologist, Dr Angel's recent activities have included an examination of the factors that affect public attitudes and opinion, coastal management, policy, and, ultimately, decision-making. Dr Angel has participated in numerous national and international research projects focusing on mariculture and has carried out research in different parts of the world. He has published numerous scientific publications on aquaculture-environment related topics in peer-reviewed journals and in books.

Francesco CARDIA – Dr Cardia is an aquaculture consultant, primarily working for private companies operating cage aquaculture activities. He graduated in 1993 from the University of Rome in Natural Sciences and Ecology and, in 2002, obtained his Ph.D. in Parasitology from the Veterinary faculty of the University of Turin, with a thesis on marine finfish parasitosis in Italian cage farms. Following this, he worked for five years at an inland freshwater aquaculture farm (cyprinids, reproduction, selection and ongrowing). From 1998 to 2003, he gained field experience in marine cage aquaculture while working full-time as a production manager with intensive cage farms producing European seabass and gilthead seabream. During the aforementioned period, he undertook a research activity together with the Chair of Parasitology of the "Tor Vergata" University in Rome. In 2002, he commenced his consulting activity in Italy, providing several cage farm companies with technical and biological advisory support, focusing on farm project and start-up, production planning, maintenance planning, traceability, and quality improvement. Since 2004, Dr Cardia has also been working as a consultant with FAO, and he continues to be involved in several activities, mainly related to cage aquaculture practices.

John FORSTER – President of Forster Consulting Inc., which has provided advice on aquaculture to private/public sector clients since 1994. Links to recent work for the United States and the Canadian Governments are: aquaculture.noaa.gov/pdf/econ/3.pdf; aquaculture.noaa.gov/pdf/econ/12.pdf; dfo-mpo.gc.ca/csas/Csas/Publications/SAR-AS/2008/SAR-AS2008_001_E.pdf. Specific areas of interest include development of offshore aquaculture, the future for large-scale farming of seaweed, and the application of commercial disciplines learned in salmon farming to new aquaculture opportunities. From 1994–2005, Dr Forster was also President of Columbia River Fish Farms, a company that he founded and developed to become the largest producer of steelhead rainbow trout in Northern America before it was sold in 2005. Previously, from 1974 to 1994, Dr Forster worked in technical and management positions for Stolt Sea Farm Washington Inc., which farmed salmon and sturgeon in the United States of America, and Shearwater Fish Farming Ltd., which farmed rainbow trout in the United Kingdom of Great Britain and Northern Ireland and provided services to aquaculture clients worldwide. Dr Forster began in aquaculture in 1965 with the Ministry of Agriculture Fisheries and Food (MAFF), the United Kingdom of Great Britain and Northern Ireland, working in research on the mass culture of prawns and the design of marine water reuse systems. Dr Forster has served on the Fisheries, Marine Fisheries Advisory Committee (MAFAC) of the National Oceanic and Atmospheric Administration (NOAA) (from 2002 to 2008), as well as a Board Director of Aquaculture without Frontiers, The Washington Fish Growers Association, and Chairman of the Global Aquaculture Alliance's Salmon Technical Committee.

Enrica FRANCHI – A researcher at the Laboratory of Lagoon Ecology, Fisheries and Aquaculture a research branch of the Polo Universitario Grossetano, a private consortium associated with the University of Siena. She was awarded a Ph.D. in Environmental Sciences and is currently a contract professor of Aquaculture and Ecological Restoration at the University of Siena. She has been working in the field of marine ecology and aquaculture for the last 15 years. Her research expertise is mainly concerned with the interaction of aquaculture on the environment and testing methods such as biodepuration, phytodepuration and integrated aquaculture to minimize negative impacts of aquaculture on the environment. Her most recent project was modelling the impact of aquaculture wastewater on the water quality of the receiving basin. Dr Franchi has participated in several European Union (Member Organization) and Italian sponsored projects on aquaculture and environment-related issues and has authored and co-authored numerous publications in peer-reviewed journals.

Marianne HOLMER – Head of Institute and Full Professor in Marine Ecology at the Institute of Biology, University of Southern Denmark. She has a Ph.D. in Marine Ecology from Odense University (now University of Southern Denmark). Her research expertise is primarily in marine benthic ecosystems in coastal zones and off-the-coast areas with particular focus on the ecosystem approach to management of marine aquaculture. Her primary area of research interests are impacts of disturbance on coastal and open-sea ecosystems, with marine aquaculture as a case study of organic enrichment. Her scientific publications (96) are all peer-reviewed, and published in well-recognized journals. She has edited one Springer book (*Aquaculture in the Ecosystem*, 2008) and written 11 book chapters. She has coordinated several European Union (Member Organization) projects on marine aquaculture, and participated in several other European Union (Member Organization) and national projects on aquaculture. She has research experience from Europe, Africa, Asia, Australia and North America through a series of short- and longer-term research projects in these areas. She is an appointed member of the Danish National Board for Oceanology and is an active member of the European Aquaculture Technology and Innovation Platform (EATIP). She teaches terrestrial and marine ecology and biological oceanography at all university levels.

Andrew JEFFS – An Associate Professor of Marine Science at the University of Auckland in New Zealand, where he teaches aquaculture. He is also a Director of Two Fathom Ltd., an aquaculture and marine environmental consultancy based in New Zealand. He has undertaken aquaculture research and consultancy work in many countries including Australia, Belize, the Caribbean, Viet Nam, Malaysia, Fiji and the United States of America. For ten years he was an aquaculture scientist for New Zealand's national aquaculture research institute, leading their major research programmes and subsequently becoming an executive manager for the institute. He played a major role in forging new working relationships with commercial aquaculture operators and with indigenous Maori for progressing aquaculture research and development. Prior to this, he was a senior officer for the New Zealand Government, responsible for coastal management, and was involved in establishing some of the first marine protected areas in New Zealand. He has published more than 100 papers in international science journals and in excess of 300 reports for commercial clients, mostly on the aquaculture of a wide range of species, including spiny lobsters, fishes, abalone, sea cucumbers, geoduck, mussels and oysters. His research and consulting efforts have resulted in many commercial outcomes, including the development of practical lobster holding and aquaculture diets, commercial lobster seed harvesting technology in New Zealand, pilot commercial spiny lobster farms in New Zealand and overseas, and mussel broodstock conditioning technology.

James McDaid KAPETSKY – Founder and Secretary-Treasurer of Consultants in Fisheries and Aquaculture Sciences and Technologies, Inc., Wilmington, the United States of America, that has been in business since 1999. As a Senior Fisheries Resources Officer in the FAO Inland Water Resources and Aquaculture Service (now the Aquaculture Branch) he specialized in promoting the use of GIS, remote sensing and mapping applications in aquaculture and inland fisheries beginning in the early 1980s. After retirement in 1999, he continued working in the same subject area, mainly on contract with FAO, but with other assignments with the United States Agency for International Development and Hatfield Consultants Ltd. In recent years he has focused on spatial approaches to improving estimates of marine aquaculture potential, particularly in the open ocean. Dr Kapetsky is an editor of GISFish, an FAO portal on spatial tools in fisheries and aquaculture (www.fao.org/fishery/gisfish/index.jsp), author of book chapters on GIS in aquaculture and inland fisheries, respectively, and a co-author with Dr J. Aguilar-Manjarrez of a number of FAO and other publications. Those dealing directly with marine aquaculture include a recent symposium presentation entitled "Spatial data needs for the development and management of open ocean aquaculture" (www.csc.noaa.gov/geotools/sessions/Thurs/ H08_Kapetsky.pdf), an FAO Fisheries Technical Paper "*GIS Remote Sensing and Mapping for the Development and Management of Marine Aquaculture*", a symposium proceedings "*Spatial perspectives on open ocean aquaculture potential in the US eastern Exclusive Economic Zones*" and a Fisheries and Aquaculture Technical Paper No. 549 entitled "*A global assessment of offshore mariculture potential from a spatial perspective*".

Gunnar KNAPP – Dr Knapp is a Fisheries Economist at the University of Alaska Anchorage. He earned both a B.A. in Economics (1975) and a Ph.D. in Economics (1981) from Yale University. Since 1981, he has been on the Faculty of the University of Alaska Anchorage's Institute of Social and Economic Research (ISER), where he has held the rank of Professor of Economics since 1992. Dr Knapp has undertaken a wide variety of research related to fisheries markets, fisheries management, the seafood industry and the aquaculture industry. Much of his work has focused on the Alaska salmon industry and changes in world salmon markets and the Alaska salmon industry resulting from the development of salmon farming. He has also studied: markets for Alaska pollock, herring, halibut, and cod; effects of the implementation of catch-share fisheries management systems in the Alaska halibut and crab fisheries; and effects of fisheries management on safety in the fishing industry. Dr Knapp recently authored two chapters of a study on "Offshore Aquaculture in the United States: Economic Considerations, Implications & Opportunities" for the United States National Oceanographic and Atmospheric Administration (NOAA) aquaculture programme, which examined the economic potential for and economic impacts of United States offshore aquaculture. Dr Knapp also teaches an Internet-based University of Alaska distance education course on fisheries economics and markets. Dr Knapp is an active participant in the International Institute of Fisheries Economics and Trade (IIFET) and the North American Association of Fisheries Economists (NAAFE) and was a founding member of NAAFE.

Yngvar OLSEN – Professor at Norwegian University of Science and Technology (NTNU), Trondhjem Biological Station, from 1995 till present. He has, since 2006, acted as Director of the Strategic Marine Focus Area at NTNU, responsible for facilitating, coordinating, and directing marine research at the university. He was earlier a senior scientist at SINTEF and is now a senior advisor at SINTEF Fisheries and Aquaculture. Professor Olsen has 25 years' experience within the main research field of aquaculture and marine plankton, including: live feed technology for marine fish larvae, lipid nutrition and first feeding of marine larvae, marine phyto- and zooplankton interactions, food web dynamics, trophic cascades, biochemical composition, nutrient cycling, and coastal eutrophication. He has published about 110 papers in international peer-reviewed journals. Scientific interests are marine juvenile production, coastal eutrophication, and environmental interactions with aquaculture. Besides his academic and research activity, Professor Olsen has been, among others, a member of the Board of Directors and a Vice President of the World Aquaculture Society (2002–2006). He has been involved in the organization of several WAS and European Aquaculture Society conferences. He acted as President of Norwegian Board for Cooperation in Marine Sciences (2001–2005). He is currently Co-chair of the Thematic Area Environmental Interaction with the Environment in the European Aquaculture Technology and Innovation Platform (EATiP) and a member of the Scientific Advisory Board of the German Leibniz Institute of Marine Sciences (IFM-GEOMAR), Kiel, Germany (2004–2012).

David PERCY – Borden Ladner Gervais Professor of Law at the University of Alberta. He holds an MA degree in Jurisprudence from Oxford University and an LLM degree from the University of Virginia. He has been a Visiting Scholar at Stanford, Virginia and the Centre for Socio-Legal Studies at Oxford and worked as a Visiting Research Scientist at FAO in Rome. He teaches Contracts, Natural Resources Law and Energy Law. He has published the leading works on Water Law in Alberta and in Canada. He acted as counsel to the Federal Inquiry on Water Policy in Canada in 1987 and worked on drafting the Alberta Water Act from 1989 to 1996. He has published three books on water law and advised governments and government agencies in six Canadian jurisdictions on water law matters. He is currently Co-Chairperson of a committee advising the Minister of Environment on water allocation issues in Alberta. David Percy's work in water law led him to develop an interest in aquaculture. In 2000–2001, David was seconded to work for FAO on problems of aquaculture in five African countries. During his period of leave, he co-authored (with Nathanael Hishamunda) a work on the Promotion of Sustainable Commercial Aquaculture in sub-Saharan Africa. In 2002, he worked as a consultant for FAO on Aquaculture Law in Namibia. In this capacity, he drafted the Aquaculture Act of Namibia (with Annick VanHoutte, FAO Senior Legal Officer, and led a national consultation on the legislation when it was in draft form. In 1995, Mr Percy won the WPM Kennedy Award for outstanding merit in Canadian Law teaching, and in 1996 he won the Rutherford Award for excellence in undergraduate teaching at the University of Alberta. In 2000, he received the Tevie H. Miller Award for Teaching at the Faculty of Law.

Neil SIMS – Co-founder and CEO of Kampachi Farms, LLC, an aquaculture research and development company based in Kona, Hawaii, the United States of America, and La Paz, Mexico. Kampachi Farms is developing commercial production of sashimi-grade Cabo Kampachi (*Seriola rivoliana*, longfin amberjack) in Mexico and other regions of the world, and is researching offshore technologies, alternative feedstuffs and new fish species for culture. Neil was also co-founder and President of Kona Blue Water Farms, the first United States integrated marine fish hatchery and open ocean mariculture operation, off Hawaii's Kona Coast, which produced more than 1 350 kg/week of longfin amberjack from an offshore site. He is Founding President of the Ocean Stewards Institute, a trade association that advocates for rational, considered development of offshore mariculture. He obtained a B.Sc. in Marine Biology/Zoology (James Cook University, Australia, 1980) and an M.Sc. in Zoology (University of New South Wales, Australia, 1990). From 1983 to 1988, he led the establishment of the Fisheries Research Division of the Cook Islands Ministry of Marine Resources, working in research and management of subsistence fisheries, and artisanal fisheries for pearl shell, *Trochus*, giant clams and finfish. At the same time, he led the research and development supporting the growth of the black pearl culture industry in the Cook Islands. Since 1993, he has been based in Hawaii, where he has led more than 40 federally funded research projects in aquaculture development, primarily focused on pearl oyster and marine fish hatchery development and open-ocean mariculture. He has led commercial ventures in Australia, Hawaii and the Marshall Islands, and has consulted for private companies, governments and regional agencies throughout the South Pacific and Southeast Asia. From 2001 to 2004, he led the development of breakthrough hatchery technology for "difficult-to-rear" marine fish, such as groupers, snappers and trevallies, which evolved into the pioneering open-ocean mariculture operation.

Piergiorgio STIPA – An aquaculturist by profession, with practical knowledge gained in different countries. He has worked on shrimp farming in Albania, and fish hatcheries and mariculture farms in Greece and Italy for more than 15 years. He is currently the technical head of both a marine cage offshore fish farm and a land-based pond fish farm in the Mediterranean (Italy). The farms are part of a wider commercial group selling top-quality fish (European seabass, gilthead seabream and meagre) in the European market with the brand “Fish from Orbetello”. Mr Stipa has a background in marine biology (he graduated in 1992 at the University of Rome) and has conducted research activities in Italy and in the United States of America (Stanford University). He is a commercial and fishing captain, being a former Italian Navy officer, and has served one year in a commercial fishing boat in the Indian Ocean. He has a commercial diving licence, with more than 10 years experience in offshore cage installations and diving operations. He has also worked and collaborated with International Organizations such as the United Nations Industrial Development Organization (UNIDO) and FAO, promoting training in environmental and aquaculture matters in countries such as Nigeria and Viet Nam. At regional level, he has collaborated in several research projects focusing on fish and mollusc farming technologies and fish quality improvement. He has recently been involved in promoting marine aquaculture activities on the island of Palawan (the Philippines), with local entrepreneurs. Nowadays, his main interests are offshore fish farming and practical applications on submerged cages and remote feeding systems.

FAO EXPERTS

José AGUILAR-MANJARREZ – Ph.D. (1992–1996) and M.Sc. (1991–1992) in Aquaculture (Aquaculture Planning and GIS) from the University of Stirling in the United Kingdom of Great Britain and Northern Ireland. He graduated in Oceanography in 1989 from the Faculty of Marine Sciences in Ensenada, Baja California, Mexico. He has worked for the FAO Fisheries and Aquaculture Department for 14 years, first as a visiting scientist (1996–1998), then as a consultant (1998–2000) and since 2001 as an Aquaculture Officer in the Aquaculture Branch (FIRA). His responsibilities at FAO-FIRA cover two different areas: GIS-related activities, and assistance to field projects on rural aquaculture in a number of countries in Latin America and Africa. Activities specific to GIS have broadly included: (i) the development of methodologies, technical papers, reviews and training materials on GIS applications to aquaculture such as FAO Fisheries Technical Paper. No. 458 (www.fao.org/docrep/009/a0906e/a0906e00.htm); (ii) the construction of georeferenced information systems such as GISFish (www.fao.org/fishery/gisfish); and (iii) the formulation, implementation and review of field projects that have a GIS and/or remote sensing component. His main current interest is in GIS and remote-sensing approaches for estimating the potential for offshore mariculture.

Nathanael HISHAMUNDA – He holds a B.Sc. in Agronomy and an Engineer of Agriculture degree from the National University of Rwanda, an M.Sc. in Fisheries and Aquaculture from Auburn University, Alabama, the United States of America, and a Ph.D. in Agricultural Economics with a specialization in Agricultural Policy, Trade and International Development from the same institution. He began his carreer as Head of Aquaculture Extension within the Rwanda Ministry of Agriculture, Livestock and Forestry in 1984. In 1986, he led the Rwanda National Aquaculture Service until he left to pursue his higher education in 1992. While at Auburn University, he served as a Research and Teaching Assistant in Agricultural Trade and Policy and in Aquaculture and Fisheries Economics, from 1993 to 1999. He joined FAO in 1999 as a Fishery Planning Analyst and currently leads the Aquaculture Economics and Policy Group, which deals with complex and diverse issues of national, regional and global importance, and coordinates the Branch assistance to FAO Members in the areas of aquaculture socio-economics, policy, planning and governance. With more than 50 publications, he has produced leading works on aquaculture economics, aquaculture policy and governance and aquaculture and food security. He has prepared aquaculture development policies and strategies, national aquaculture development plans and has contributed to the preparation of legal and regulatory frameworks for sustainable aquaculture development for numerous countries in Africa.

Jiansan JIA – He has been working with FAO as Chief of the Aquaculture Branch since 1998. Before joining FAO, he worked for the Government of China for more than 20 years, holding several leading positions with provincial and central government authorities, in both national and international agriculture, fisheries and aquaculture development (e.g. Director General, China National Corporation for International Cooperation in Agriculture, Livestock and Fisheries; Director General, International Cooperation, Ministry of Agriculture; Executive Vice-President, China National Fisheries Corporation; Deputy Director General, Bureau of Fisheries; Vice Governor, Wujiang County, Jiangsu Province). During the past 12 years, he has devoted himself to sustainable development of aquaculture at global and regional levels by leading the FAO Aquaculture Branch based in Rome. He was one of the leading organizers of the Conference on Aquaculture in the 3rd Millennium held in Bangkok in 2000, and promoted the establishment and advancement of the FAO's Committee on Fisheries (COFI) Sub-Committee on Aquaculture. Mr Jia was the Co-Chair of the International Organizing Committee of the Global Conference on Aquaculture 2010.

Blaise KUEMLANGAN – He has been a Legal Officer in the Development Service of the Legal Office of FAO since 1996. He holds a Masters (LLM) in International and Comparative Law, Kent School of Law, Chicago, and a Bachelor of Laws (LLB) from the University of Papua New Guinea. Prior to joining FAO, he was a Senior Legal Officer with the State Solicitors Office of the Papua New Guinea Attorney General's Department, where he provided legal advice and assistance to government agencies including the Department of Foreign Affairs, Civil Aviation, Trade and Industry, Environment and Conservation and Fisheries and Marine Resources. He was also involved in fisheries enforcement, including the prosecution of offences. In the FAO Legal Office, he specializes in the international law of the sea in the field of fisheries and the development of national fisheries and aquaculture law through technical advice and field assistance to FAO Members in many regions of the globe. He has drafted or contributed to the review and development of the aquaculture laws of many developing countries. His typical annual work includes the provision of assistance and advice on the legal aspects of fisheries and aquaculture normative work, projects and consultations of FAO's Department of Fisheries and Aquaculture.

Alessandro LOVATELLI – A marine biologist and aquaculturist, he obtained his B.Sc. and M.Sc. degrees at the universities of Southampton and Plymouth (the United Kingdom of Great Britain and Northern Ireland), respectively. His first experience with FAO dates back to 1987, working as a bivalve expert attached to an FAO/UNDP regional project. His subsequent FAO assignment was in Mexico, working on a regional aquaculture development project funded by the Italian Government. From 1993 to 1997, he worked in Viet Nam, Somalia and then again in Southeast Asia. In Viet Nam, he headed the aquaculture and fisheries component of a large European Union (Member Organization) project developing, among other activities, ten regional aquaculture demonstration, training and extension centres. In Somalia, he acted as the lead aquaculture and fisheries consultant for the European Commission. Following an additional year in Viet Nam as one of the Team Leaders under the Danish-funded Fisheries Master Plan Project, he was recruited by FAO as the Aquaculture Advisor attached to the FAO-EASTFISH project based in Denmark. In 2001, he once again joined the FAO Department of Fishery and Aquaculture in Rome. The main activities he is currently focusing on are marine/offshore aquaculture development, transfer of farming technologies and resources management. Mr Lovatelli has coordinated and co-authored numerous FAO technical reviews and papers, mainly focused on marine aquaculture development.

Doris SOTO – Obtained her B.Sc. in Limnology from the University of Chile in 1975 and her Ph.D. in Ecology (aquatic ecology/food webs) in the Joint Doctoral Program between San Diego State University and University of California in Davis, the United States of America, in 1988. She worked as a Professor at the Fisheries and Oceanography Department at Austral University in Puerto Montt, Chile, until 2004. She was also an Adjunct Scientist at the Institute of Ecosystem Studies in Millbrook, New York (the United States of America) from 1999 to 2005. Up to 2005, she was involved in research activities on aquaculture environmental management and nutrient cycling of salmon farms and other aquaculture systems, both in freshwater and marine environments. She has carried out research to evaluate the effect of escaped salmon and trout on aquatic ecosystems. She joined FAO in 2005, where she has been leading the development of a framework for an ecosystem approach to aquaculture. She is the focal point for climate change impacts on the aquaculture sector. She has conducted extensive fieldwork in Latin America and worked with FAO partners in the Mediterranean Sea on various aspects of mariculture and the environment. She has published numerous scientific papers and reports, and has led different types of projects.

Rohana SUBASINGHE – A Senior Aquaculture Officer at the Fisheries and Aquaculture Department of FAO. He is specialized in aquaculture development and aquatic animal health management. Since his graduation in 1980 from the University of Colombo, Sri Lanka, he has worked in all parts of the world, with most experience in Asia. He joined FAO in 1994 and took responsibility in implementing numerous projects on aquaculture and aquatic animal health at national, regional and international levels. Among others, at FAO, he is also responsible for analysis of trends in aquaculture development globally. A former teacher at the University of Colombo and the Universiti Putra Malaysia, Mr Subasinghe earned his Ph.D. at the University of Stirling. He has been responsible for initiating major policy changes in aquatic health management in relation to aquaculture in Asia and globally. He currently serves as the Technical Secretary to the Sub-Committee on Aquaculture of the Committee on Fisheries (SCA-COFI) of FAO, the only global intergovernmental forum on aquaculture.

Diego VALDERRAMA – He holds a B.Sc. in Marine Biology from the Universidad Jorge Tadeo Lozano (Colombia), an M.Sc. in Aquaculture/Fisheries from the University of Arkansas at Pine Bluff (UAPB) (the United States of America), and a Ph.D. in Environmental and Natural Resource Economics from the University of Rhode Island (the United States of America). His expertise is in the economics of aquaculture and marine resources. In addition to numerous peer-reviewed articles, he has co-authored three book chapters on aquaculture economics issues. As a Master's student, he investigated the production economics of shrimp farming in Central America, catfish farming in the southeast of the United States of America, and the economics of aquaculture effluent regulation. His doctoral work examined a variety of issues in marine resource economics. His work has also addressed the economic potential and implications of offshore aquaculture development in the United States of America. In 2009 and 2010, he joined FAO as an Aquaculture Officer (Economics) in the Fisheries and Aquaculture Department, where he contributed to the Department's work on social and economic aspects of policy and strategy development to ensure sustained livelihoods for all beneficiaries in aquaculture. He is currently an Assistant Professor at the Food and Resource Economics Department at the University of Florida (the United States of America), where he teaches and conducts research on marine resource economics and international economic development.

Annex 5 – Group photograph

From left to right: Alessandro Lovatelli, José Aguilar-Manjarrez, John Forster, Jia Jiansan, Doris Soto, Dror Angel, Blaise Kuemlangan, James McDaid Kapetsky, Adolfo Alvial, Neil Anthony Sims, Marianne Holmer, Francesco Cardia, Nathanael Hishamunda, Andrew Jeffs, Diego Valderrama, Enrica Franchi, Yngvar Olsen, David R. Percy, Gunnar Knapp, Piergiorgio Stipa (missing: Rohana Subasinghe).

Contributed papers

A review of opportunities, technical constraints and future needs of offshore mariculture – temperate waters

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ABSTRACT

This paper reviews the status, investment and market considerations, and technical constraints to the development of offshore aquaculture in temperate regions of the world. It explores trends in production and discusses the importance of farming seafood products that are "affordable" if they are going to meet mass-market demand. In this respect, it notes that there are relatively few dominant (i.e. one million metric tonne/year) species and speculates on why this might be so. It reviews technical constraints to the future development of offshore aquaculture, among them engineering and operational challenges, questions of species selection, juvenile supply, aquatic animal health issues and the availability of suitable feed ingredients. It also considers issues of predator control, environmental impact and the critical importance of adequately trained people. It concludes by suggesting that offshore marine aquaculture will only develop to its full potential if enthusiasm for the idea is backed by an equal measure of political will. By presenting a long-range vision for this, the Food and Agriculture Organization of the United Nations (FAO) can help society to understand its benefits and make a case for it that cannot be denied.

INTRODUCTION

In 2006, worldwide production of fish, shellfish and marine plants from marine aquaculture was 36.2 million tonnes. This compares with 81.9 million tonnes harvested by the world's capture fisheries in the same year, for a combined total harvest of food from the oceans of 119.2 million tonnes (FAO, 2009). This represents about 1.7 percent by weight of man's total food supply.[1]

[1] Calculated by assuming total world food production of about seven billion tonnes (Global dataset of aquaculture production [quantity and value] 1950–2008. Released in March 2010, by the Fisheries and Aquaculture Statistics and Information Service, FAO).

In considering the future for offshore marine aquaculture, these figures prompt two observations and a question. First, marine aquaculture already contributes substantially to the world's ocean harvest, despite the fact that most of it occurs in nearshore waters. Second, though the oceans cover 70 percent of the Earth, we derive remarkably little of our food from them. Which prompts the question: is this inevitable and could the oceans be used to produce more of our food if we learned to farm offshore in some of the vast area that is available?

This is not a new idea. The possibility has been recognized by governments, industry and researchers since the 1960s, but progress has been slow due to technical challenges and to regulatory and political constraints in some countries. This paper considers opportunities for and technical constraints to offshore marine aquaculture in temperate waters, defined as those to the north and south of the Tropics of Capricorn and Cancer. The main countries presently engaged in aquaculture within this region are the People's Republic of China (northern part), Republic of Korea, Japan, Australia (southern part), New Zealand, Republic of Chile, United Mexican States (northern part), North America and Europe.

"Offshore mariculture" is a term that is not easy to define precisely. For the purposes of this discussion, it is defined as marine aquaculture that occurs in locations that are fully exposed on at least one quarter. In other words, farm structures have to be able to withstand the full force of an ocean storm should this occur. Since this applies to most of the oceans' surface, it embraces most of the future opportunity, but it also embraces large stretches of near shore waters along exposed coastlines and, realistically, this is where the first advances in offshore aquaculture will be made.

As well as technical challenges, offshore mariculture faces environmental, regulatory and financial constraints, which are the subject of other papers in this analysis. Insofar as solutions to all of them require political will, as well as science to solve them, creation by FAO of a coherent and imaginative vision for the future of offshore marine aquaculture will be helpful and this review is timely.

CURRENT STATUS

Table 1 summarizes global marine and brackish water aquaculture production in 2007 in terms of the major product categories. It shows that most production by weight (76.9 percent) consisted of marine plants and bivalve molluscs, while shrimp and finfish contributed most of the value (61.5 percent). Shrimp are mostly grown in the tropics in coastal ponds and are not considered further in this paper because, being tropical, they are outside its scope and they are unlikely candidates for offshore mariculture anyway.[2] By contrast, marine plants, bivalve molluscs and finfish are mostly grown in temperate waters and are candidates for offshore mariculture, and are the subject of the discussion that follows.

TABLE 1
Weight and value of the main marine and brackish water aquaculture product categories in 2007

Product category	Total production (mt)	Value (US$ '000)	Value/kg
Plants	14 784 148	7 504 680	0.51
Bivalve molluscs	12 848 400	12 642 221	0.98
Crustaceans	3 612 894	14 683 128	4.06
Finfish (brackish water + marine)	4 693 025	17 542 697	3.74
TOTAL	**35 938 467**	**52 372 725**	**1.46**

Source: Global dataset of aquaculture production (quantity and value) 1950–2008. Released in March 2010, by Fisheries and Aquaculture Statistics and Information Service, FAO.

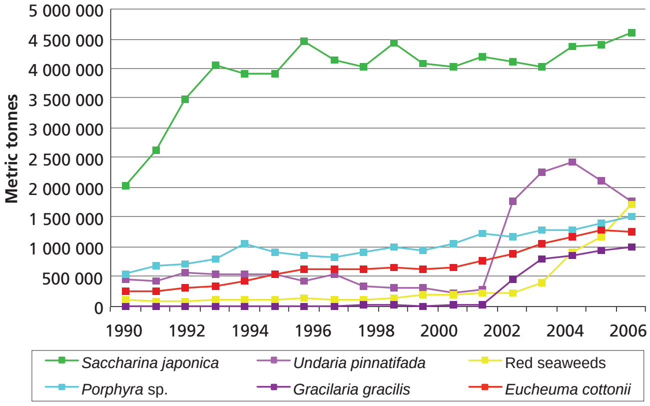
[2] At least this would be the conventional wisdom. However, recent trials in the Sea of Cortez (Mexico) have shown surprisingly good performance of shrimp in cages, sufficient to encourage further development.

It is noteworthy that, in each category production is dominated by relatively few species with one species being highly dominant (Figures 1, 2 and 3). The Japanese giant kelp, *Saccharina japonica*, makes up 31 percent of all marine plants that are farmed, while *Crassostrea* species (mostly *C. gigas*) contribute 33 percent of all farmed molluscs, and Atlantic salmon (*Salmon salar*) contributes 30 percent of marine and brackish water farmed finfish, with salmonids in total contributing 39 percent. Collectively, the species or species groups represented in Figures 1, 2 and 3, contribute respectively 80.3 percent, 76.7 percent and 65.2 percent of all brackish water and marine plants, molluscs and finfish that are farmed worldwide.

This dominance of only a few species or species groups points to the idea that even though many hundreds of aquatic species have been domesticated by farming, only a few of them may have what it takes to become major farm species. If, for example, "major" is defined as exceeding one million tonnes per year production, only one finfish species out of hundreds that are farmed meets this definition, namely the Atlantic salmon, which dominates the finfish product category, like *Saccharina japonica* and *Crassostrea gigas* dominate the marine plant and mollusc categories. The significance of this is discussed further in the section on species selection.

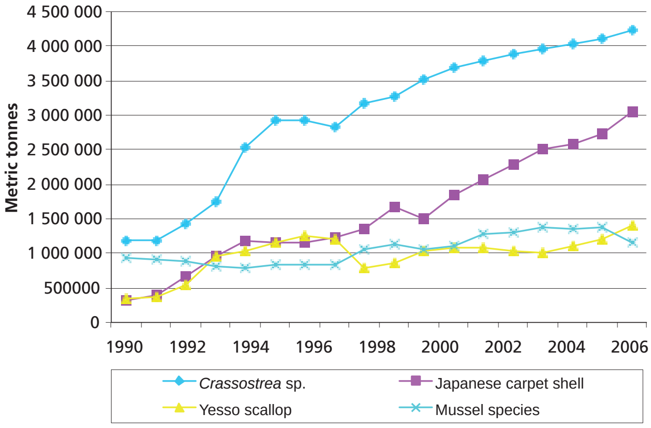
Figure 4 summarizes production trends for each of the major product categories since 1990 and shows how volume growth of marine aquaculture has been driven by plants and molluscs, in contrast to freshwater aquaculture, which has been driven by finfish. The significance of this is discussed in Section 3.2 below in the context of expected increases in future demand for seafood and how demand for different product categories will govern the nature of future offshore aquaculture industries.

FIGURE 1
Trends in production of important marine and brackish water marine plant species since 1990 in tonnes



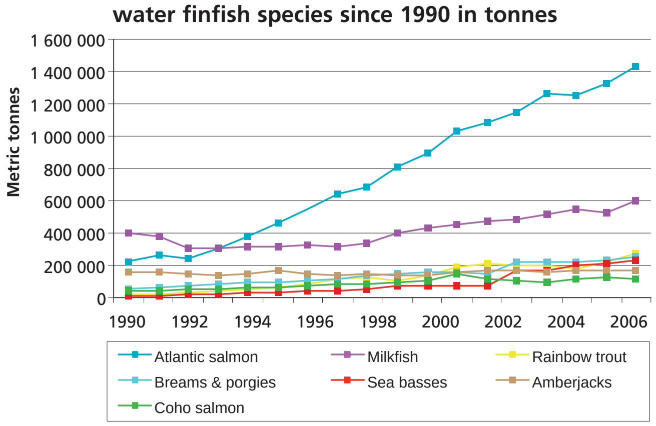
Source: Global dataset of aquaculture production (quantity and value) 1950–2008. Released in March 2010, by the Fisheries and Aquaculture Statistics and Information Service, FAO.

FIGURE 2
Trends in production of important mollusc species since 1990 in tonnes



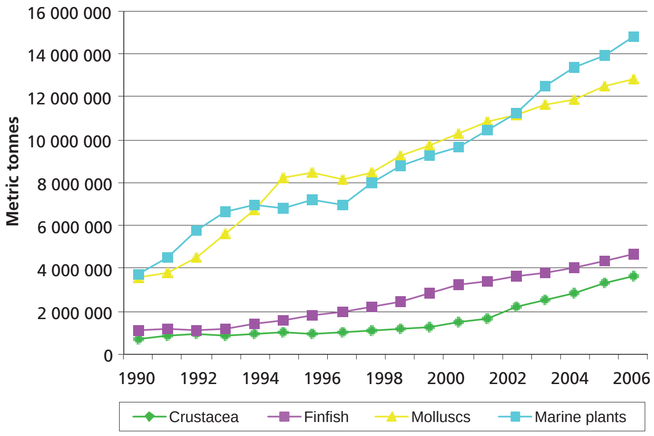
Source: Global dataset of aquaculture production (quantity and value) 1950–2008. Released in March 2010, by the Fisheries and Aquaculture Statistics and Information Service, FAO.

FIGURE 3
Trends in production of important marine and brackish water finfish species since 1990 in tonnes



Source: Global dataset of aquaculture production (quantity and value) 1950–2008. Released in March 2010, by the Fisheries and Aquaculture Statistics and Information Service, FAO.

FIGURE 4
Trends in production of the different categories of all marine aquaculture products since 1990 in tonnes



Source: Global dataset of aquaculture production (quantity and value) 1950–2008. Released in March 2010, by the Fisheries and Aquaculture Statistics and Information Service, FAO.

INVESTMENT AND MARKET CONSIDERATIONS

Investment

All successful mariculture, be it nearshore or offshore, for fish, molluscs or marine plants, requires clean water and must have shore-based infrastructure and services available to support it. Assuming these elements are in place, then the biggest challenge in moving offshore is how to design and install equipment that can withstand storm driven waves and currents and provide a safe working platform for farm workers. Though culture methods for finfish, bivalve shellfish and marine plants are quite different, challenges of anchoring and operation at sea are common to all and there is a general need for engineering sophistication in all offshore aquaculture. Some key considerations include:

- heavy-duty moorings in deep water;
- offshore systems for the containment or support of the aquatic crop;
- sea-going work boats equipped with cranes and fish pumps;
- offshore feed storage and feed distribution systems;
- mechanization of as many husbandry tasks as can be mechanized;
- remote monitoring and control systems; and
- development of large farms in order to capture economies of scale.

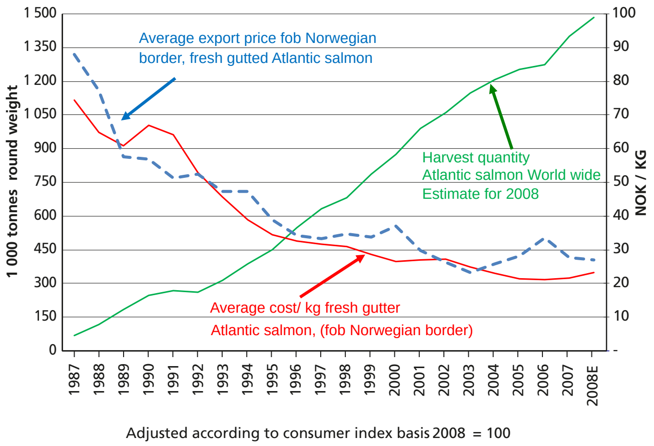
From FAO's standpoint, this need for engineering sophistication may have a bearing on how assistance programmes are structured, because the technology and investment will most likely have to come from developed countries; lack of both having been identified as bottlenecks by developing countries.

Market definition

Since technology development will be driven by actual and expected market demand for different types of seafood, it is helpful to consider the market before contemplating what technical challenges there may be. It is widely assumed that demand for seafood is running ahead of supply as production from the world's capture fisheries stagnate and the pace of aquaculture growth slows (FAO, 2009). But most discussion of this uses the terms "fish" or "seafood" to mean finfish, shrimp and molluscs collectively, while marine plants are usually excluded. Yet, it is clear from Table 1 and Figure 4 that the main products from marine aquaculture today are marine plants and bivalve molluscs, with shrimp and finfish comprising a relatively small proportion based on live weight. If offshore marine aquaculture is to play a role in bridging the gap between expected seafood supply and demand, what sort of seafood should it produce? Are each of the market categories freely substitutable one with the other, or are they categories that have their own market characteristics that will follow different paths?

From a resource use and technical point of view, marine plants and bivalve molluscs have the huge advantage that they do not have to be fed with compounded feeds, and this is a powerful incentive to increase their production. However, it is not certain that demand for them offers a comparable incentive. Marine plants are eaten widely in Asia, but not much in the rest of the world, while many bivalve molluscs tend to be speciality products eaten as starter dishes rather than as "centre of the plate" items. Moreover, the edible meat yield from bivalves is often quite low, so that production reported on a live weight basis exaggerates their true food value. While these are broad generalizations with undoubted exceptions, the lack of clear definition between categories in market forecasts for seafood makes it more difficult to judge what market forces will drive future offshore aquaculture production. Put another way, better understanding of the exceptions and recognition of the need for category specific market development is an important part of trying to figure out what the best long-term opportunities for offshore marine aquaculture may be.

FIGURE 5
Volume, cost and price trends of farmed salmon



Source: The Norwegian Seafood Export Council / Kontali. Myrseth, 2009.

Demand for seafood is also price sensitive. Figure 5 shows how, as worldwide production of farmed salmon increased from about 75 000 tonnes to 1.6 million tonnes between 1987 and 2008, the selling price fell.

Arguably, price reductions are now starting to level off, but the point is that even at production levels of only a few hundred thousand tonnes per year, prices had to come down in order to encourage more people to buy salmon. Though it is widely assumed that aquaculture will have to produce many millions of tonnes of new seafood to keep pace with the expected demand, such assumptions are rarely accompanied by projections of the likely prices that consumers will be willing to pay for the extra volumes. Instead, there is often talk of "niche markets" and "high value species" that promise rich returns for those who can produce them. However, the lesson from salmon farming is that these markets are relatively small. If aquaculture is to produce the millions of tonnes of new seafood thought necessary, it will have to be priced to meet the value expectations of the mass market. Farmed salmon serves as a helpful benchmark in this regard.

More than "seafood"

It is also appropriate to consider the future for offshore mariculture in the wider context of overall global food supply. In a recent media release related to a Forum on "Feeding the World 2050", FAO stated "*Producing 70 percent more food for an additional 2.3 billion people by 2050 while at the same time combating poverty and hunger, using scarce natural resources more efficiently and adapting to climate change are the main challenges world agriculture will face in the coming decades.*" Duarte *et al.* (2009) emphasize similar concerns and discuss how marine aquaculture might be part of the solution. If offshore mariculture is to contribute to the alleviation of world hunger, what would it have to do?

In round numbers, the total weight of food produced in the world today is about seven billion tonnes. Of this, roughly six billion tonnes are plants and one billion tonnes are animal products, a ratio of 6:1. The same ratio for all of the world's aquaculture is about 1:3 and for the world's capture fisheries, it is 1:53. These ratios suggest that we need to look mostly to plants, not animals, for solutions to the challenges of global food supply and, for offshore mariculture, this means marine plants or seaweeds.

The People's Republic of China grows most of the marine plants in the world today-about 9.8 million tonnes out of a world total of 15 million tonnes. Of the 9.8 million tonnes, about four million tonnes is the brown kelp *Saccharina japonica,* which was farmed in 41 000 hectares of coastal waters in 2004 (Chen, 2006). Assuming kelp is 80 percent water, this gives a dry weight production of plant matter of 19.5 tonnes/hectare. Extrapolating, that means that six billion tonnes (the weight of plants produced each year by agriculture) could be grown in 308 million hectares of ocean space, which is less than one percent of the ocean's total surface. In fact, because conversion to dry weight of *Saccharina* skews this calculation in favour of agriculture, the area of ocean required to grow an exactly comparable amount of plant biomass is probably substantially less than one percent.

That is important. If there really are concerns about how it is going to be possible to feed everyone in 2050, the idea that the world's production of plant biomass might be doubled by farming marine plants in less than one percent of the oceans is surely one that should be taken seriously. Moreover, since seaweeds can be grown without using land or freshwater, and even without fertilizers in some places, farming them should be taken even more seriously. Large-scale seaweed farms might also be used to remove excess nutrients that cause phytoplankton blooms and other problems in some coastal waters.

Market opportunities

The above suggests that offshore mariculture offers three general opportunities. First, there will be a need for more finfish because demand is expected to increase and fish landings from the world's capture fisheries will remain stagnant. In so far as many fish have intrinsic market value (Table 1), this suggests that commercial incentives to develop and expand farming of finfish offshore will be strong and will encourage continued development, though the end products will have to be "affordable" if large volumes are to be produced.

Second, there will be similar incentive to develop offshore farming of shellfish, though this may be confined to a limited number of species such as mussels and scallops, which have broad market appeal and may be best suited to floating methods of culture. In addition, there will be environmental incentives to encourage bivalve shellfish farming because they feed themselves, being the only means we have to harvest the vast natural phytoplankton productivity of the sea.

Third, there is apparent potential to increase the production of marine plants, but little immediate market incentive to do so. Left to market forces alone, this is an opportunity that might go unrealized and a question for FAO and the national governments it advises is, should their respective natural resource agencies intervene to encourage development? It is not hard to imagine western consumers accepting the idea of "marine vegetables" that offer nutrition, variety, value and a food source that leaves a gentle footprint on the Earth (MacArtain *et al.*, 2007). In turn, this would provide a market incentive to farm them and, as techniques were perfected and volumes built, this could lead to the development of other uses such as animal feed ingredients (Yoshimatsu *et al.*, 2005) or biofuel (Aisawa *et al.*, 2007; Chynoweth, 2002; Roesijadi *et al.*, 2008).

Presently, there is interest in several western countries in the idea of integrated multi-trophic aquaculture (IMTA) where marine plants and shellfish are grown "downstream" of marine fish farms in order to reuse some of the wastes (nutrients) that they release. Because these projects will produce limited quantities of marine plants, it is to be hoped this may inspire parallel programmes to develop markets for them. However, though IMTA may offer a practical way to introduce the idea of farming marine plants, it is really looking at it the wrong way round. They should be a primary source of biomass, as in agriculture, not a secondary product used to clean up wastes. The vision for this form of offshore aquaculture should be bigger, and a focus on demonstrating and promoting the food value of marine plants for people would seem to be the most likely way to get such a vision accepted. In this respect, an American company has recently trademarked the name "*Kelp – the Virtuous Vegetable*™" (Ocean Approved Inc.; www.oceanapproved.com), which illustrates the imagery that could be used in promotional efforts.

TECHNICAL CONSTRAINTS

Offshore mariculture presents numerous technical challenges, many of which have been faced and met in nearshore aquaculture, albeit in less challenging circumstances. They range from engineering challenges to species selection and juvenile supply, to matters relating to environmental impact and environmental service costs. For offshore mariculture to succeed on a scale that makes a meaningful impact on human seafood supply, answers are needed to all of them. However, the transition from nearshore to offshore will be gradual and answers will evolve over time. Sometimes people talk about a "blue revolution" in the context of marine aquaculture, but development of aquaculture offshore will be evolutionary rather than revolutionary and aquaculture's needs and significance might be better understood by critics if it was to be explained as a "blue evolution", with adaptation and improvement that will continue indefinitely. The important thing for all to realize is that this involves trial and error and unless there is tolerance for error, such evolution cannot occur.

Engineering

The two biggest engineering challenges in offshore mariculture are storm events at sea and the cost of anchoring equipment at depth. Mooring with traditional multi-anchor systems becomes expensive at anything much more than 75 m of depth and this greatly restricts where offshore farms may be located. Single point mooring systems have the potential to increase the range of depth options, though they are not used much presently and they prompt justified concern about dependence on just one mooring line. However, their use would expand the range of possible offshore site options and their further development is an engineering priority.

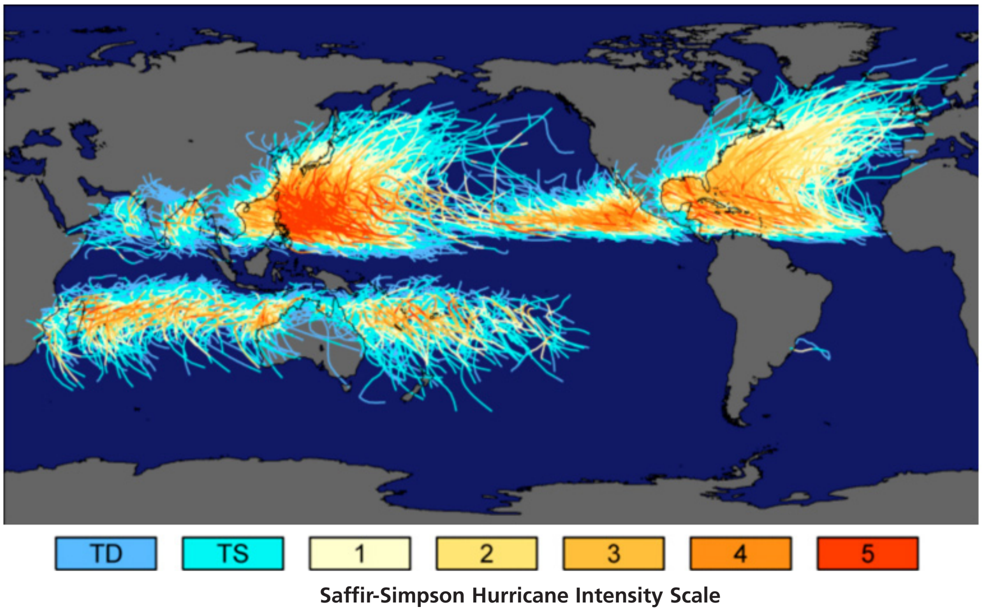
Eventually, for open ocean aquaculture to achieve its full potential and if the constraints imposed by depth are to be overcome, self-positioning, free-floating systems must be developed. Initial work on concepts has been started at the Massachusetts Institute of Technology (Handwerk, 2009), though this is very preliminary and it will likely take many years yet before commercial prototypes are available. Meantime, there are many shallow water areas in the world where offshore mariculture can be started, and it is best for now to concentrate effort there and accept the limitations imposed by moorings. The immediate engineering challenge, therefore, is waves created by ocean storms and there are two most probable solutions.

The first is to locate farms in parts of the world where storm events are rare and the spacial review that is a parallel part of the present proceedings will be especially helpful in this respect (Kapetsky, Aguilar-Manjarrez and Jenness, 2012). Figure 6 is a map that shows where major tropical storm activity is concentrated in the world and shows how the search for suitable locations might begin to be narrowed down.

More detailed mapping is required to pinpoint areas that are all or mostly free of both major and minor storms. The Mediterranean coast of the Kingdom of Spain is an example of such an area where a number of farms are anchored in locations with exposure to the east of several hundred kilometres. Finfish farms like the one shown in Figure 7, have operated there with conventional floating plastic high density polyethylene (HDPE) cages for several years without any major weather damage.

However, benign weather is not the only driver for offshore aquaculture development. Good coastal infrastructure and ready access to markets are equally important, and there are many parts of the world, including the west coast of Europe, most of the United States of America, including the State of Hawaii, and the Republic of Korea, where these offer good reasons to develop the industry, despite potentially stormy weather. This has stimulated development of new designs of offshore cages that can withstand major storm events. Concepts range from submersible, rigid framed structures to flexible, floating support collars that ride rather than resist the waves (Figure 8) and there is enough experience now to think that offshore farming in these areas is possible, though cost and operational practicality are still constraints (Loverich and Forster, 2000; Forster, 2008).

FIGURE 6
Storm tracks at sea to show where tropical storms are concentrated



Source: http://mapscroll.blogspot.com/2009/05/visualizing-global-warming.html

FIGURE 7
Culmarex SA finfish farms off the east coast of Spain

COURTESY OF CULMAREX SA

There are similar challenges in the offshore farming of bivalve shellfish and marine plants. Lovatelli (1988) described structures used for the suspended farming of the Yesso scallop (*Pactinopecten yessoensis*) in Mutsu Bay in northern Japan using submerged longlines from which netting containers are hung and in which the scallops are placed (Figure 9). Longline systems are naturally ocean compliant and are well suited to growing crops that attach directly to ropes such as mussels and some marine plants. Consequently, they have been adapted for the offshore farming of mussels in the Mediterranean, Atlantic Canada, New Zealand and northeastern United States of America (Langan, in preparation) and are used extensively in Asia for farming the kelp *Saccharina japonica* (Figure 10).

In this respect, aquaculture methods for the offshore farming of bivalve shellfish and marine plants are relatively further advanced than they are for finfish and more

FIGURE 8
Examples of offshore finfish cages

COURTESY OF ACQUA AZZURRA SPA

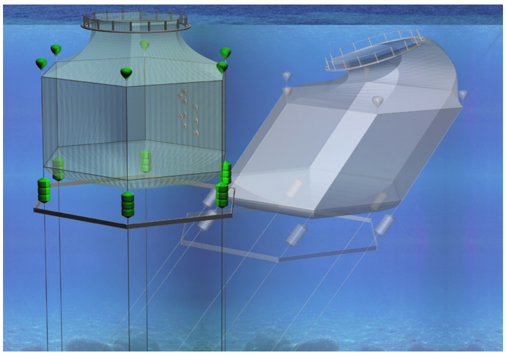
Bridgestone cage – flexible surface collar

COURTESY OF ITTICA OFFSHORE DEL TIRRENO SPA

Platform cage – resists waves by strength of structure

COURTESY OF ACQUA AZZURRA SPA

FarmOcean cage – semi-submersible, reduced surface exposure



COURTESY OF REFA MED

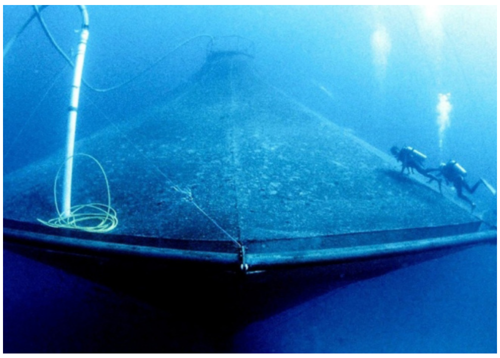
Refa Med Tension Leg cage – flexible, float tensioned moorings

COURTESY OF OCEAN FARMS TECHNOLOGIES INC

Aquapod – geodesic sphere, submersible

COURTESY OF FRANCESCO CARDIA

Sadco Shelf cage – rigid frame, submersible



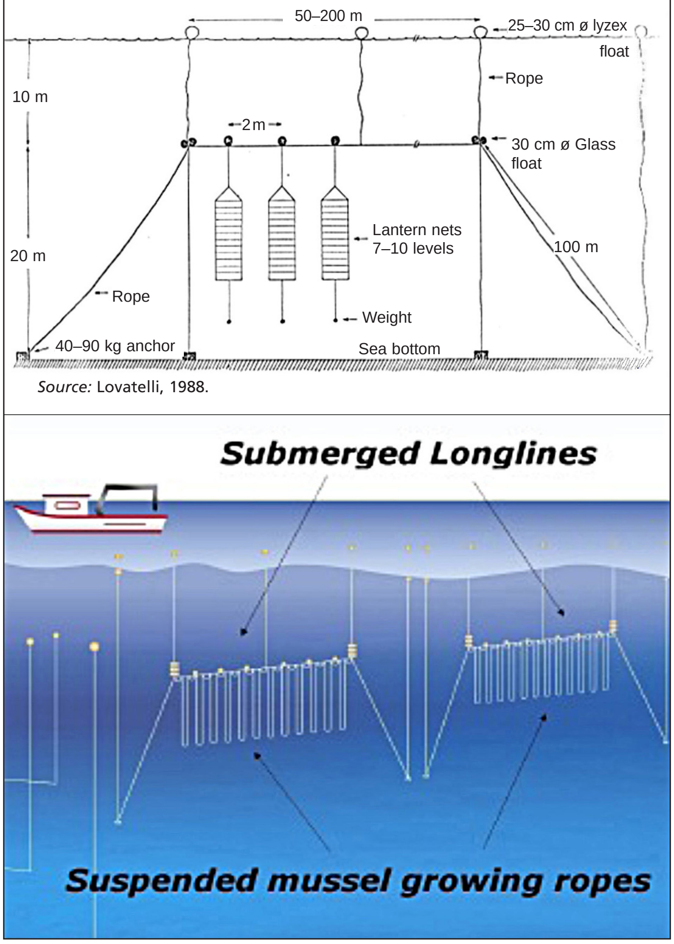
COURTESY OF OCEANSPAR LLC

SeaStation cage – central spar and rigging, submersible

COURTESY OF SUBFLEX LTD / ANAT LYNN

Subflex cages – submersible single-point mooring flexible net cage system

FIGURE 9
Longline culture of scallops and mussels



Source: Lovatelli, 1988.

COURTESY OF UNIVERSITY OF NEW HAMPSHIRE

immediately adaptable for technology transfer to developing countries. The difficulties with them may relate more to the cost of production and selling prices for the products than to engineering feasibility. In addition, marine plants have to be able to capture light, so farms for them tend to occupy greater surface area than farms for finfish or shellfish and this will magnify equipment challenges in the open sea. This requirement for light also means that submersion, as a way of avoiding heavy seas, is a less likely solution for marine plants than it is for finfish and bivalves.

From a historical point of view, it is worth noting that between 1968 and 1990 a programme in the United States of America that became known as the U.S. Marine Biomass Program, was one of the first serious attempts to test the offshore farming of marine plants. It was conceived by Howard Wilcox who, with others, dreamt of ocean food and energy farms that would produce marine plant biomass that could then be processed, like terrestrial crops, into multiple food and energy products. Given impetus by the first world oil crisis of the 1970s, it became mostly a bioenergy project and was funded generously by the United States Department of Energy and related agencies. Chynoweth (2002) summarizes the work in considerable detail and describes how it eventually petered out as oil flowed freely again in the 1980s and early 1990s and a sense of crisis lapsed into complacency. A more recent review (Roesijadi *et al.*, 2008) looked at this work in the context of current enthusiasm for biofuels, as well as other possible uses for marine biomass and concluded that higher value applications, such as the direct use of marine plants as food for people, offered the most immediate opportunities for development.

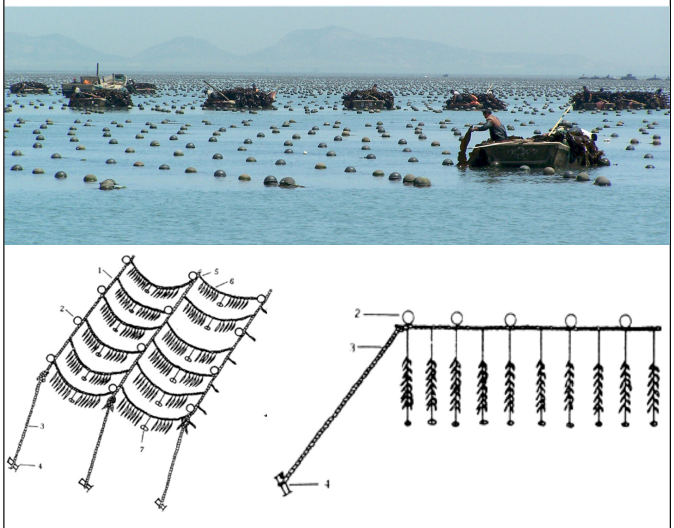
Operations

Though engineering solutions for the offshore containment of aquaculture crops have been shown to be feasible, there is still a long way to go to integrate them into safe, large-scale operating systems where all the key tasks involved in aquatic husbandry are done cost efficiently. These include feeding, grading, harvesting, cleaning and monitoring of farm functions, all of which have to be done at sea under conditions that may often be difficult and dangerous. Lack of such an integrated capability is the main reason that salmon farmers have held back from expanding offshore up to now, leaving the burden of offshore development to less experienced farmers of new aquaculture species in locations where sheltered sites are not available and where the potential for high selling prices justifies the risk. As a result, progress has been slower than it might have been, had salmon farming companies been more involved.

Feeding and livestock handling

However, progress has been made. The University of New Hampshire, for example, has built a prototype, ocean compliant feed storage and feeding system (Figure 11), that promises to deal with one of the biggest challenges, namely the routine operations involved in transporting feed to a fish farm and feeding the fish. When this is fully mechanized, remotely controlled and, potentially, solar or wave powered, it will reduce both the labour requirements on the farm and the frequency of trips needed to deliver feed.

FIGURE 10
Farming of marine plants in China



Source: Chen, 2006; FAO, 1989.

COURTESY OF CHEN JIAXIN

FIGURE 11
A 20-tonne prototype ocean farm feeder

COURTESY OF UNIVERSITY OF NEW HAMPSHIRE

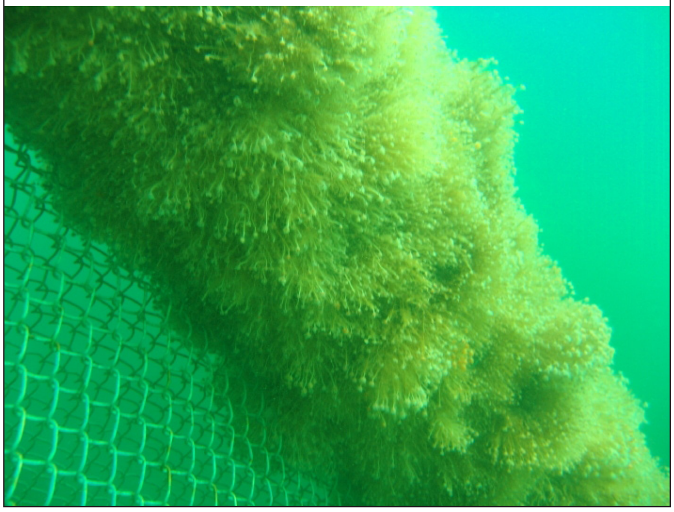
Grading and harvesting are also labour intensive activities that are more difficult to do offshore, especially if there is much wave activity. For finfish, this usually means that they first have to be crowded so they can be graded or moved into the harvest system. For shellfish, it means lifting them on to the deck of a boat so they can be worked on there. Crowding fish in offshore cages is sometimes done by installing a fixed partition in the cage and rotating it at the surface so the fish are crowded into one segment. Though it is not done yet, it also seems that it would be feasible to tow cages inshore for harvesting, if a system was designed for easy detachment and reattachment of moorings.

In all cases, the less stock handling that has to be done the better. It is always difficult, weather dependent and stressful on the stock. One strategy to eliminate the need for grading is to stock farms with juveniles that are large enough and sufficiently well-graded that they do not need to be sorted again until they are harvested.

Marine biofouling

Marine biofouling is another aspect of marine aquaculture that demands attention and controlling which is often labour intensive. It tends to be site specific in relation to intensity and species and varies with season. For bivalves, mechanical cleaning on the deck of a boat is the most common cleaning method, sometimes combined with dipping in a fluid that kills some of the biofouling organisms. In finfish farming, cleaning strategies include replacement of the fouled net with a clean one and washing of fouled nets onshore, air drying by lifting part of the net out of the water, or cleaning *in situ* with a surface or diver operated net cleaning device. These methods are often used in combination with net coating materials that deter fouling organisms; cuprous oxide being the most commonly used active ingredient.

FIGURE 12
The copper nickel mesh is suspended from a HDPE pipe, which is extensively fouled in contrast to the mesh which is not



COURTESY OF RICHARD LANGAN

Another interesting antifouling strategy for certain designs of finfish cage is to rotate them at the surface, thereby, allowing sections of the net to dry in turn so that fouling organisms die before they have a chance to grow significantly. In order to do this, the cages must be completely enclosed and designs such as the Aquapod™ and SeaStation™ (see Figure 8). These type of cages are well suited to this fouling removal method. Fully enclosed cages that can be submerged may also be able to be moved between different depths as a way to disorient fouling organisms.

Any methods for fouling control that require handling of the stock or gear will be more difficult to do offshore than nearshore and much more difficult if there is any sort of wave activity. For this reason, impregnation or coating of nets or lines with materials that deter fouling has important advantages, except that there is concern about the use of copper based materials because of potentially toxic effects on non-target organisms. Research is in progress on alternative anti-fouling compounds including natural antifouling metabolites derived from marine plants (Center for Marine Biotechnology and Biomedicine [CMBB], undated), materials that inhibit biofouling physically and on netting material made from a copper nickel alloy. While the latter is still based on copper, it does not slough particles into marine waters like cuprous oxide based coatings and its intrinsic strength may confer other benefits (Figure 12). The Collective Research on Aquaculture Biofouling (CRAB) Project in Europe is another effort to find new solutions for marine biofouling (CRAB, 2006).

System monitoring

Finally, there is a need to monitor certain farm functions including:

- mechanical system integrity – condition of moorings, attachments, nets, etc.,
- stock condition, behaviour and health,
- feed consumption in the case of finfish,
- stock mortality,
- water quality,
- presence of predators, and
- surveillance for intruders or vandals.

With modern technology, most of these things can be done using probes, robots and cameras that can be controlled and tracked remotely. Even things like fish health may be susceptible to remote monitoring, one day, using micro tags that monitor and transmit data about physiological functions. However, they all have to be robust enough to work in offshore conditions, so sophisticated probes and electronics alone will not be enough.

Cumulatively, all of the above operational tasks come under the heading of what farmers call "husbandry" and the long-term goal for offshore mariculture should be to integrate them into farming systems that are mechanized and remotely controlled as far as possible. Above all, there must be emphasis on reducing the need for people to have to work under dangerous conditions at sea, especially if diving is involved, because it is inherently dangerous and expensive. If offshore mariculture is to fulfil its promise and develop on a large-scale, it must find ways to use people for oversight of mechanical systems rather than physical performance of farm operations as is the case now.

Species selection

Over the last 50 years several species have been selected as especially good candidates for marine aquaculture and have become dominant (Table 2). These are the "million tonne per year" species, or species groups. There are 12 of them, which in total make up 70.8 percent of production from all of marine and brackish water aquaculture. Nine of them are temperate water species and six of them are marine plants. Because they have been so successful, it is important to understand why. Some of their key attributes include:

- they are good to eat, or have value for chemical extraction in the case of some of the marine plants;
- general tolerance of farm conditions can mean natural resistance to parasites and disease, tolerance of handling and crowding, ready acceptance of dry feed for fed species, or a calm behavioural demeanour that curbs stress;
- ready availability as seed stock from either hatcheries or natural settlement;
- they are fast growing, or relatively fast growing;
- adaptability to farming outside, as well as within their native range;
- in most cases, they have been genetically improved by selective breeding, extending their advantages even further over new candidate species; and
- edible meat yield, or recovery, of fed species is high enough to make production of value added products economically feasible.

This prompts several questions about species selection for the future:

- Is this concentration on only a few species fortuitous or is it because, like corn, rice and wheat, or chickens, pigs and cows, they have special farm attributes?
- Do any of the new species that are being tested in aquaculture have characteristics that will allow them to become similarly dominant?
- Are there species that are waiting to be "discovered" for aquaculture? If they have the right characteristics, these need not be species that are well known in fisheries or the market.
- If really good species for aquaculture are limited in number, will it be necessary to transfer those that are good further outside their native range? If so, what precautions are needed? FAO's Technical guidelines on aquaculture certification minimum substantive criteria # 49 address this question by saying that "*exotic*

TABLE 2
The "million tonne per year" species and species groups in marine and brackish water aquaculture

Marine plants	Scientific name	Production in 2007 (mt)
Japanese kelp	*Saccharina japonica*	4 613 104
Wakame	*Undaria pinnatifda*	1 765 470
Red seaweeds	Red seaweeds	1 728 475
Laver (Nori)	*Porphyra*	1 510 634
Zanzibar weed	*Eucheuma cottonii*	1 247 945
Warty *Gracilaria*	*Gracilaria gracilis*	1 003 892
Molluscs		
Pacific oyster	*Crassostrea gigas*	4 233 829
Japanese carpet shell	*Ruditapes philippinarum*	3 044 057
Yesso scallop	*Pactinopecten yessoensis*	1 412 797
Mussels	Several species	1 163 448
Shrimp and finfish		
White legged shrimp	*Penaeus vannamei*	2 296 359
Atlantic salmon	*Salmo salar*	1 433 030
TOTAL		**25 453 040**

Source: Global dataset of aquaculture production (quantity and value) 1950–2008. Released in March 2010, by the Fisheries and Aquaculture Statistics and Information Service, FAO.

species are to be used only when they pose an acceptable level of risk to the natural environment, biodiversity and ecosystem health", which is reasonable, but does not specify what "low risk" means (FAO, 2011).

- Even within their native range, should aquaculture species be selectively bred, given concerns about interbreeding with wild stock? FAO's criteria, cited above, are silent on this.
- What about farming transgenically modified (GMO) species? There is no need of them presently, but will this change, as it is changing in terrestrial agriculture?

The evidence from recent years suggests that the concentration on only a few species may not be fortuitous. Numerous species of aquatic animals are farmed in many parts of the world and some have been farmed for many years on quite a large scale, but they have not broken through to the million tonne per year level. The criteria for species selection in aquaculture should be reviewed, especially for those species where there are such high hopes. It is easy to be enthusiastic about seafood variety and upscale market niches but, if the long-term goal for marine aquaculture is to fill an expected seafood deficit of millions of tonnes per year, maybe this can only be done if we find and focus on a few species that have demonstrably superior culture characteristics.

Also, based on the record, it is at least a reasonable proposition that if all new aquaculture activities are to be based on farming only native species, progress will be slower than if they are not. It is noteworthy that, all the "million tonne per year" species in Table 2 are already farmed widely outside their native range. For this reason, it would be helpful if the risks posed by new species introductions and/or genetically improved aquatic stocks were better understood. By encouraging such work, FAO could help to ensure that absence of scientific information does not become a reason to hold otherwise valid and potentially important aquaculture development back.

FAO could also encourage research into the production of all female and sterile farm stocks. Triploid oysters and rainbow trout are used routinely now in commercial farming but triploidy has not yet worked so well in other aquatic farmed species. A new project in Europe (www.salmotrip.stir.ac.uk) will re-look at the feasibility of growing triploids of Atlantic salmon, earlier attempts having been unsuccessful. In the Kingdom of Norway, a project to test performance of triploid Atlantic salmon over the full production cycle put smolts to sea in the fall of 2009. Preliminary results show better growth in freshwater, but an increase in deformities (M. Dalen, personal communication, 2009).

Juvenile supply

For the dominant marine aquaculture species listed in Table 2 juvenile supply need not be a limitation. Hatchery or natural seed collection practices are well established and can be replicated as needed. Juvenile supply is a bigger constraint for some of the newer species of interest because hatchery capacity is limited and/or the hatchery rearing process is less reliable. Availability of established, domesticated broodstock of some of these species may also be a limitation. There are three general ways in which juveniles (seed) are produced, examples of which are shown in Figure 13.

i. They are captured from the wild. This is still standard practice for mussel and scallop seed where it is not considered threatening to wild populations. However, it is of ecological concern where it is still done in certain shrimp farming situations, and for yellowtail farming in Japan and tuna farming worldwide, and it is being phased out.

ii. Production in fertilized ponds where blooms of phytoplankton and zooplankton provide feed for larvae hatched from eggs in a hatchery. This method is used extensively in Asia and is successful in producing a wide variety of species. An advantage is that juveniles can feed on a variety of natural plankton, though there is little or no control of what species these are.

iii. Production in modern hatcheries where phytoplankton, rotifers and *Artemia* are provided as feed and where all other aspects of the rearing process are controlled as

FIGURE 13
Examples of hatchery and nursery systems

COURTESY OF JOHN FORSTER

Seedling hatchery for the giant kelp *Saccharina japonica* in Yantai, China

COURTESY OF JOHN FORSTER

Salt water pond for producing marine finfish in southern China

COURTESY OF RICHARD PRICKET

A modern marine finfish hatchery for European seabass and gilthead seabream in Spain

COURTESY OF RICHARD PRICKET

A marine finfish nursery for European seabass and gilthead seabream in Spain

closely as possible. Such control is an advantage compared to open ponds, but the limited range of live feeds may be inadequate for some species and may compromise juvenile quality.

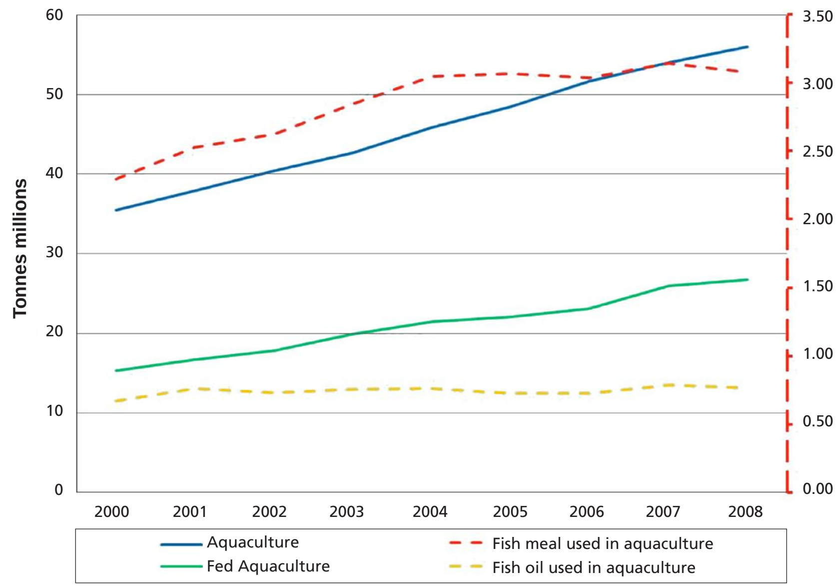
In all cases, the optimum size at which juveniles should be stocked in offshore farming facilities is still open to question. There is a natural inclination to want to do this as early as possible when the juveniles are small, because growing them larger in land-based facilities can be costly and transporting them to the cages becomes more costly as they get bigger. However, very small juveniles or seedlings may be more vulnerable to disease and parasites than larger ones. One of the reasons why salmon farming may have been successful is that the salmon life cycle requires that fish be kept in hatcheries until they reach 60–120 g live weight before transfer to salt water as smolts. Eventually, this may prove to be the best production strategy for all species in offshore farms, where it will be simplest to stock large seedlings, or juveniles, and harvest them when they have reached market size without any handling or sorting during the rearing process.

A reliable supply of good quality juveniles is obviously a vital precursor to any offshore marine farming activity. Where capacity does not exist, FAO assistance with the establishment of captive broodstock and the construction and operation of hatcheries and nurseries could be a valuable part of any support programme. This could also include help with breeding programmes to select stocks with favourable farm characteristics.

Feeds

Though there is concern about the high level of use of fishmeal and fish oil in some aquaculture feeds, availability of these ingredients does not constrain offshore farming presently, because there is so little offshore production. However, this will not be so indefinitely and research to find alternatives is necessary and is now showing

FIGURE 14
Global aquaculture growth and use of fishmeal and fish oil from 2000–2008



Source: Shepherd, 2009.

results (Turchini, Tortensen and Wing-Keong, 2009; Tacon and Metian, 2008). This is illustrated by the fact that there has been little or no increase in the global use of fishmeal and fish oil in aquaculture feeds in recent years, despite of increases in the worldwide aquaculture production (Figure 14).

However, people are now beginning to question whether any feed ingredient that could be eaten directly by humans should instead be fed to farm animals and there is concern about pressure to produce more of these ingredients because it may lead to new environmentally damaging agricultural development. FAO could help in this area in two ways.

The first is to become much better than we now are at life cycle assessment (LCA), because it holds the promise of being able to make objective comparisons of efficiency between different food producing activities. From a feed efficiency point of view, there are reasons to think that when aquaculture is compared in this way with intensive animal farming on land it may show up rather well. For example, as poikilotherms, aquatic livestock burn less energy than terrestrial livestock in order to grow and, therefore, produce less greenhouse gases (GHGs). However, full LCA requires accounting not just for energy and GHGs, but for all resource and environmental service inputs, as well as the food value derived from them. Studies such as The Global Salmon LCA (Ecotrust, 2010), Ellingsen and Aanodsen (2006), Ayers and Tyedmers (2008) or Pelletier *et al.* (2009) are helpful starts, but there is a long way to go yet before shrimp and finfish farmers might be able to make an unequivocal case for their businesses based on demonstrated life cycle efficiency.

This gets to the heart of present discussion about sustainability. This word is now used so widely in all kinds of different contexts that its meaning has become blurred. It has become a concept rather than a measurable, comparative attribute, and it is used carelessly to claim sustainability for human activities that are clearly not sustainable in the long-term. "*You can't manage what you can't measure*" is a business cliché and LCA is the best tool there is presently by which some measure of sustainability might be made. A LCA methodology that allowed comparative measurement of ecological efficiency between different food producing processes, including aquaculture, would help to bring objectivity to discussion that is now often subjective and may lead us in wrong directions.

The second is the idea that marine plants might be grown and processed into feeds for finfish so that marine aquaculture could become self-sustaining. In the raw state, seaweed nutrients are protected by indigestible cell walls, or are chemically bound in a way that diminishes their potential nutritional value. Processing or bio-refining the raw plants to make the nutrients they contain more available may be a solution. Japanese scientists are leaders in this field using fermentation and enzyme digestion to release spheroplasts and chloroplasts from *Porphyra* that led to improved survival and nutrient retention, when included in feeds for black and red seabream at three percent and five percent, respectively (Khan *et al.*, 2008; Kalla *et al.*, 2008). Though these are low levels of inclusion, perhaps they point to how marine plants might be used in aquaculture feeds in future, in turn providing the market incentive to increase the farming of them.

Stock health

Diseases and parasites are serious threats in all aquaculture. Offshore, they may be less of a threat than nearshore due to better water quality conditions, though they may also be harder to control. However, it is essential that adequate treatment methods are developed and available for the inevitable occasions when they will be needed. This applies mostly to finfish and there are several preventative and treatment approaches, all of which are used in nearshore aquaculture and some of which will be usable offshore. They include:

i. Good fish husbandry, which is an all embracing term to mean good water conditions and feed, moderate stocking densities, clean cages, prompt mortality removal, careful handling, etc. It is fundamental good aquaculture practice and there are examples of farms where, if such practices are followed diligently, treatments for fish health problems are rarely needed.
ii. Bio-security, which includes obvious things like not bringing diseased juveniles on to a farm, disinfection of equipment that has been used on another farm, and care in harvesting to ensure no spillage of blood. It may also include single year class stocking and area management agreements with neighbouring farms so that all of them stock, harvest and fallow on the same schedule.
iii. Selection of species that are naturally resistant or are less vulnerable to stress induced disease because they adapt well to farm conditions.
iv. Stocking of large juveniles that are in the peak of condition when they are stocked. Too little is known yet about how to measure and manage the physiological condition of juveniles reared in hatcheries.
v. Inclusion of pre- and probiotics and immunological stimulants in feeds. Today, many claims are made for various substances, some no doubt exaggerated, but there seems to be an emerging consensus that this approach is helpful (Fish Farmer, 2009).
vi. Use of vaccines, which have proved their efficacy against bacterial diseases in salmon. Vaccines are also available now for virus diseases like Infectious Salmon Anemia (ISA) and for some other finfish species. Since they may also be effective against certain parasites, this is a field where there is almost unlimited scope for improvement and it is a priority.
vii. Medication, either in the feed or administered as a bath treatment. Use of antibiotics and other medicines in feed is an environmental concern in aquaculture, especially if it leads to overuse. However, it is and likely always will be one of the tools that fish health professionals need to use. Bath treatments for external and gill parasites are also important fish health management tools, but they may be difficult to administer offshore.
viii. Selective breeding of naturally resistant strains. The Norwegian Institute for Food Fisheries and Aquaculture Research reported recently that some strains of salmon

are more easily infested with sea lice than other strains and breeding from them could save the salmon farming industry millions of dollars a year (Nofima, 2008). Work has also been done to breed salmon strains that are naturally resistant to the Infectious Pancreatic Necrosis virus (IPN) (Aquagen, 2008).

ix. Changing cage depth, or simply providing very deep nets so that fish have a choice where they swim, may help in some circumstances. This has been used to avoid the effects of phytoplankton blooms on salmon farms in British Columbia (Canada) and there are reports that it may also help with control of sea lice.

Most of these approaches come under the heading of prevention rather than treatment and they apply to shellfish and marine plants even more so than they do to finfish because vaccine and medication options for them are not available. For this reason, species selection and selective breeding for stocks that have natural resistance to disease is important. For example, the success of *Crassostrea gigas* as a farmed oyster in Europe is in large part due to its greater resistance to the protozoan parasite, *Bonamia,* to which the native oyster *Ostrea edulis* is susceptible (FAO, 2004).

Predators

In aquaculture, as in agriculture, predation on farm stocks by wildlife is a problem unless protective measures are taken. The problems and solutions tend to be species and region specific and there is general concern about reliance on lethal methods of control, especially of avian and mammalian predators.

Since finfish are already contained in cages, entry of predators is a matter of making sure that the cage meshes are strong enough to resist them, and this is not always easy with large predators like sea lions that can tear holes in nets. For this reason, special predator nets are often used that provide an added layer of protection around the main fish containment net. However, these provide another surface for marine fouling, which reduces water flow and adds to the drag coefficient of farm structures. In some circumstances also, because predator nets are difficult to change and have larger meshes, farmers tend to leave them in the water for extended periods of time, when they may create habitat for transitional stages of certain fish parasites.

Predator nets will be even more problematic to use offshore where handling of all farm gear is more difficult. Therefore, alternative strategies are needed and the most likely is the use of materials for the primary fish net that are stronger than nylon and strong enough to resist predators with a single barrier. New materials such as Kikko Net (www.fukuina.com/netting/kikko_net), Dyneema® (www.dsm.com) and Aquagrid® (www.aquagrid.net) are now used in some nearshore cages and, though more expensive, are likely to become the preferred primary netting materials in offshore cages. There are also cages such as the Aquapod™ (see Figure 8), which are clad in predator resistant, plastic coated metal mesh.

Shellfish predators are mostly smaller than those that prey on finfish and include a number of invertebrates such as starfish, crabs and snails. Farmers often protect shellfish against them by enclosing the farm stock in plastic net bags or tubes, or in nylon "pearl" or "lantern' nets". As in finfish farming, these materials attract marine fouling and this must be cleaned, which is more difficult to do offshore. Since most bivalve shellfish need protection when they are small, a preferred strategy for offshore production may be to use nursery farms for the early vulnerable stages, only transferring them to offshore structures when they are predator resistant. This same idea was discussed earlier in the context of juvenile finfish supply.

With regards to marine plants, numerous organisms such as sea urchins and herbivorous fish graze on them and they may damage small-scale cultures or slow growing seaweed species. For example, grazing by large halfmoon perch destroyed kelp plants within a few days at one experimental California location where kelp farming was being tested as part of the US Marine Biomass Program (North, 1987; Chynoweth, 2002). Ask (undated) also notes that slow growing seaweed species grown in nearshore farms for carrageenan production are vulnerable to predation by *Siganus* sp., which nip the growing tips of the seaweed thallus, reducing the plant growth for a week or more until the plant heals itself. Predators do not seem to be a problem in large-scale production of fast growing seaweeds where growth greatly exceeds grazing demand.

Environmental impact

Environmental issues in offshore mariculture are discussed separately in this FAO review and therefore it is inappropriate to go into detail here. However, it is appropriate to note that campaigns against the development of offshore aquaculture, conducted mostly based on environmental concerns, have held development of the industry back. This is especially so in the United States of America that might otherwise have provided technical leadership. Therefore, environmental issues and concerns about offshore aquaculture are a serious constraint to its development. It would be helpful if FAO could offer international perspective on this by weighing precautionary concerns about environmental impact against precautionary measures that must be taken to assure future human food supply.

Integrated multi-trophic aquaculture (IMTA) is considered by some to be a possible solution to some environmental concerns though, in reality, it responds only to the release of nutrients and this is probably one of the lesser environmental concerns offshore. Development and evaluation of IMTA should be encouraged, but it should not be assumed an improvement until it is fully tested. There are questions, for example, about biosecurity risks in creating verdant habitat close to fish farms and about the design of farms for marine plants in offshore conditions, which, until they are proved seaworthy, might be more of a hazard than a help. Evaluation should also consider simply allowing released nutrients to be assimilated naturally in the marine ecosystem. It is not obvious why growing marine macrophytes close to finfish farms as part of a multi-trophic system would be considered preferable to natural growth of phytoplankton further away, unless their production pays for itself both economically and in terms of life cycle costs such as energy consumption.

Trained offshore personnel

All forms of aquaculture require specialized skills and additional skills are required offshore for navigation and safe working practices. Fishers have the latter skills and, if they are willing, are almost certainly capable of learning aquaculture skills. However, this involves a change of mindset and most likely a change in status from independent owner operator of a fishing boat to employee of an aquaculture company. It cannot be assumed that such changes are easily made and, therefore, training programmes that understand this and work to achieve the transition will help offshore aquaculture to develop more surely.

A constraint is that because there are so few offshore aquaculture facilities operating worldwide it will be difficult to provide trainees with practical experience and development of demonstration offshore farms would be helpful in this respect. Such farms have been instrumental in demonstrating many new farming technologies and it seems likely that they could be equally helpful in developing and demonstrating methods for offshore mariculture.

CONCLUSION

In 2003, The Economist began an editorial about ocean aquaculture with this: *"If modern agriculture was invented today, it probably wouldn't be allowed"* (The Economist, 2003). Of course, agriculture was invented thousands of years ago and the gradual, evolutionary development of modern agriculture since then, aided by land ownership laws that put the rights of the land owner on an equal footing with society, has been generally accepted.

The circumstances in which ocean aquaculture is being invented are quite different. Our present well-being in the developed world means that production of more food from the sea is not a necessity in the same way that agriculture was necessary, while development of new technologies today happens so quickly that the consequences of mistakes can be more serious. Moreover, society is beginning to understand the importance of balancing human needs with those of the ecosystem and, as the "owner" of the ocean space that would be farmed, it is the sole arbiter of how it should be used; there being no private ocean ownership laws to provide counterweight.

So, an undeniable case for ocean mariculture has not yet been made and until it is, the political will needed to encourage it will be undermined by public ambivalence and even hostility. All of the technical constraints discussed above can be overcome if society decides that offshore mariculture is something it needs. On the other hand, if it decides it is something it can do without, the obstacles may begin to seem insurmountable. FAO can help make the case by standing back from national squabbles about resource allocation, market competition and coastal conservation, to look at the Earth and its people as one and to present a long range, global vision of what ocean aquaculture might accomplish and might look like, say, 100 years from now. This would put ideas for development in context and provide scope and direction to programmes designed to test them. This paper has highlighted the following questions that might be addressed in creating such a vision.

Marine plants

There is a huge apparent potential to increase our vegetable biomass supply by greatly expanding the farming of marine plants. As noted, the present ratio of plant to animal production in all of aquaculture 1:3. If instead, this was 6:1, as it is for terrestrial agriculture, we should now be producing 270 million tonnes of marine plants per year, instead of 15 million tonnes per year. Therefore, a key question is, should transition to plant based, self-sustaining marine aquaculture be part of the long-term vision for ocean farming and, if so, is there merit in pointing out how little of the oceans' surface would be needed to achieve it?

Market definition

People talk of a future seafood supply deficit, but is this of marine plants, bivalve molluscs, shrimps, finfish, or all of these and, if the latter, in what proportion? Better definition of the future market mix will help to clarify what a future marine aquaculture industry must do in order to meet demand.

Competitive value

If offshore aquaculture is to contribute substantially to human well-being, its products must offer competitive value. The history of the farmed salmon industry illustrates the importance of this as production volumes build. This makes it extremely important to select species for aquaculture with attributes that make competitive pricing possible.

Which species?

Today, only 12 aquaculture species, or species groups, are produced at a level of more than a million tonnes per year, and the record of accomplishment of developing "new" species is mixed. Is it possible that the excitement that accompanies seafood in all its varieties will mislead us into thinking it can all be farmed when, in fact, it may not be possible to duplicate such variety at a cost that meets mass-market expectations of value? Moreover, might this mean that like chickens, pigs and cows on land, offshore mariculture will be driven by relatively few species that are farmed worldwide?

Industry critical mass

The efficiency needed to make aquaculture products affordable will depend on large-scale development and industry concentration. This will allow the establishment of service companies that help to make primary producers more efficient. The need for this critical mass gives advantage to those countries that already have well established near shore aquaculture industries, and may make it even harder to start offshore mariculture in some developing countries. How can this handicap be overcome?

Ecological efficiency

Should ecological efficiency be factored in to future projections of market mix? If so, what information is needed in order to be able to decide on the best balance? An important part of this is determining the long-term implications of producing animals that are fed on feeds made from ingredients that could also be food for people. Equally important is determining the "carrying capacity" of marine waters to support increased aquaculture production. Overall, it means more definitive Life Cycle Assessment. Is such analysis capable of providing the precision needed to make good decisions about a future product mix?

Help for developing countries

The engineering, financing and management demands of offshore mariculture will likely necessitate corporate investment and mean that it is driven by technology and companies from developed economies. What role can developing countries play in this and how can they be helped to participate? Might publicly sponsored demonstration farms serve as R&D platforms, training locations and as a less threatening way than commercial development to introduce the offshore aquaculture idea?

Is it necessary?

Finally, do we really need to find ways to increase the food yield from the oceans in order to sustain human well-being, or is it an ecological extravagance? In the developed world, we have reached a state of well-being where such a question can be asked. A long- range vision for ocean aquaculture must not only be able to answer it affirmatively, but must be able to show also how it can be done in balance with the marine ecosystem and in a way that is less intrusive than agriculture has been on land.

Offshore mariculture will only develop if enthusiasm for the idea is backed by an equal measure of political will. By addressing these questions and developing a long-range vision, FAO can help society to understand its benefits and make a case for it that cannot be denied.

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A review on technical constraints, opportunities and needs to ensure the development of the mariculture sector worldwide – tropical zone

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ABSTRACT

This paper provides an overview of the technical constraints, opportunities and needs for enabling the development of open water mariculture in the tropical regions of the world. Global mariculture production has been growing rapidly in recent years. In many areas where this activity has expanded rapidly there is increasing pressure on the available coastal space for mariculture and conflict with other coastal resource users. This has resulted in initiatives to move mariculture further from the coast and most often also into deeper water. These open waters are generally more exposed to wind and waves, and therefore, require more advanced aquaculture technology and infrastructure in order to remain effective. Two approaches have emerged. Firstly, the evolution of existing commercial mariculture technologies mostly through more robust construction of coastal mariculture systems making them suitable for open waters. These mariculture systems are being increasingly commercialized, with the higher infrastructure and operating costs offset by greater scale of production and the increased use of remote control technologies. Secondly, the development of novel open water mariculture technologies, which mostly involve large-scale structures that can be submerged to avoid the wind and wave exposure encountered in offshore situations. While many of these novel mariculture systems are only in the design stages or are being operated on an experimental basis, an increasing number are coming into commercial-scale production. Most of this technological and commercial development is occurring in the cooler water regions of the world where the majority of large-scale commercial mariculture production currently occurs, especially for finfish. However, there is significant potential for the development of mariculture in the world's tropical zone, with many countries within this zone now actively encouraging mariculture development. There are some examples of companies taking advanced commercial mariculture technologies, including open water technologies, into the tropical zone. In general, the tropical region of the world's oceans provides some significant advantages for aquaculture. Most importantly, the waters are warm and usually with a limited seasonal fluctuation, which can deliver very fast growth rates in species suited to these conditions. Throughout much of the tropical zone, wind and wave conditions tend to be less, than in cooler waters, especially in an equatorial belt which is largely free from tropical cyclones. Tropical waters also tend to have lower nutrient levels and phytoplankton production, which probably makes many open water areas in the tropical zone unsuitable for macroalgal and filter feeding shellfish mariculture production. However, such conditions are very appropriate for finfish farming, which has been at the forefront of much of the open water aquaculture development internationally. Large-scale commercial mariculture of tropical finfish, even in coastal waters, is beginning to emerge with work on a variety of suitable species. Advanced knowledge and greater experience of suitable tropical finfish species, such as cobia (*Rachycentron canadum*), will provide a stronger basis for advancing open water mariculture in the tropical zone. Further advances could be achieved for developing nations in the tropical zone by encouraging the improvement of mariculture governance and planning, as well as assisting with technological and personnel capability in open water mariculture. It is recommended that these areas should be the focus of future international initiatives in collaboration with developing nations.

INTRODUCTION

Aquaculture has been the fastest growing animal food producing sector in the world for many years (FAO, 2009). In the early 1950s, the global aquaculture production amounted to less than 1 million tonnes per year and by 2006 this had grown to 51.7 million tonnes with a value of USD78.8 billion, an annual growth rate of nearly 7 percent.

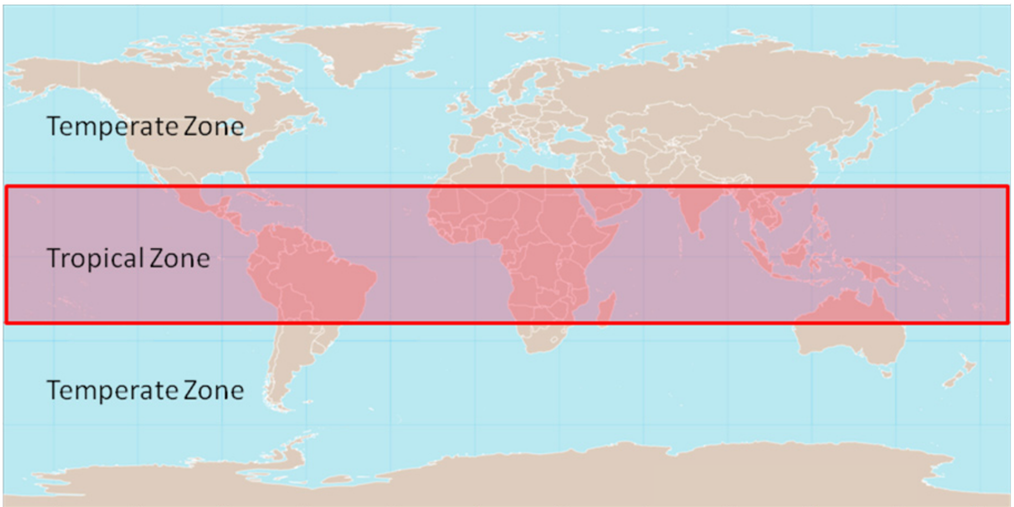
Mariculture makes up nearly half of global aquaculture production, estimated at 31 million tonnes in 2006 (including aquatic plants, but excluding brackish waters). However, since 2000, growth in the production volumes from global mariculture has been slower (5.4 percent average annual increase) than freshwater (6.5 percent) and brackish water (11.6 percent) aquaculture (FAO, 2009). However, the trend is reversed for the growth in the value of production; mariculture (8.3 percent average annual increase), freshwater (7.8 percent) and brackish water (5.9 percent) aquaculture, which reflects the higher value per unit weight of mariculture production. Partly, as a consequence of these trends, there is strong interest from developing countries in expanding mariculture.

A number of developing nations have approached the Food and Agriculture Organization of the United Nations (FAO) for assistance with mariculture development, especially relating to the development of off-the-coast and offshore mariculture. There is a wide range of issues associated with moving mariculture further from the coast, including technical feasibility, regulatory and environmental concerns, as well as potential conflict with other resource users.

In response to these requests, FAO has launched a project aimed at gathering global information on the potential for the development of off-the-coast and offshore mariculture by considering technical, biological, spatial, environmental, socio-economic, legal and policy issues. This paper represents part of the first phase of the project, reviewing technical issues relating to the sustainable development of off-the-coast and offshore mariculture in the tropical zone of the world.

The scope of this review is to examine the current mariculture technologies for the global tropical zone and to identify and discuss the current developments and emerging issues, especially in relation to the future opportunities for development of open water mariculture in developed and developing nations. The aim of the review is to help with

FIGURE 1
Tropical and temperate zones of the world for the purposes of this review paper



Source: Modified Wikimedia Commons image.

the development of recommendations and broad guidelines on technical issues that need to be investigated to ensure the expansion of mariculture in the future, and to identify priority actions that could be coordinated at the international level particularly by agencies, such as the FAO, to assist lesser developed nations.

This paper is one of the reviews that have been prepared and has been integrated to form a global synthesis of knowledge for open water mariculture that will help to underpin proposals for a global programme for the development of open water mariculture.

For the purposes of this review paper the following definitions apply:

Tropical zone – region of the Earth between the Tropic of Cancer and Capricorn, as opposed to the "temperate zone" in between these and the (Ant-) Arctic circles (Figure 1).

Off-the-coast – mariculture locations that are between 500 m to 3 km from the coastline, less than 50 m water depth, and have up to 3–4 m significant wave height.

Offshore – mariculture locations that are greater than 2 km from the coastline, but generally remaining on the continental shelf, but are greater than 50 m depth, and have greater than 5 m significant wave height.

Open water aquaculture – refers to both off-the-coast and offshore mariculture.

Significant wave height – the average wave height (trough to crest) of the largest third of waves encountered at a site.

Global trend toward off-the-coast and offshore mariculture

The global aquaculture industry is growing rapidly and evolving in response to key factors, such as changes in technology, markets, economics, species availability, feed sources, disease, public perceptions and environmental constraints. Many of these key factors are important considerations for the future development of offshore mariculture within the tropical zone.

Mariculture in most parts of the world, especially in developing countries, usually begins on a small scale in sheltered inshore waters using simple aquaculture technology, such as pens in shallow water, where the contained farm stock are easily accessible under a range of weather conditions and can be closely observed for security reasons (Ackefors, Huner and Konikoff, 1994; Beveridge, 2004). As mariculture activities have required more space to accommodate growth, or they have come into conflict with other coastal activities, they have increasingly moved further away from the coast into less sheltered waters. This has required improvements in mariculture technology to withstand the greater physical forces (winds, waves, currents) and the greater depth of water in which farms are located. In general, the greater the distance offshore that a mariculture activity is located, the more complex the aquaculture technology required, the greater the capital investment required for establishment, and the higher the ongoing operating costs. Despite these economic disincentives, in the past 25 years commercial-scale mariculture has increasingly been expanding further from the coast mostly using modifications of existing farm technology and husbandry that has firstly been developed in inshore waters (Beveridge, 2004). To a large extent it has been made economically viable by a concomitant increase in the scale and efficiency of mariculture, which has been sufficient to offset the greater capital and operating costs. As a result, off-the-coast mariculture is now commonplace in many developed countries and is increasingly being utilized in developing countries for the expansion for mariculture.

Moving mariculture even greater distances from the coast is more challenging, both technologically and economically. For more than 30 years there has been extensive research and development, as well as some commercialization of offshore mariculture. The offshore mariculture technology that is emerging is markedly different to that used for off-the-coast mariculture, which has evolved directly from inshore technology. While the utility of some offshore mariculture technology appears to have largely been proven, the commercial application of the technology has been slow and remains limited in extent, and is most often being applied at the margins of the "offshore", i.e. two kilometres from shore (O'Hanlon *et al.,* 2003). The reason for this probably relates to economics, especially the substantial establishment costs, risks from adverse natural events, and uncertain financial returns (Beveridge, 2004; Stickney, 2009). However, like the development of the preceding inshore and off-the-coast mariculture, once offshore technology has become standardized and common practice, its application will undoubtedly increase and the entry barriers, such as establishment costs, will decrease.

There are strong influences that are encouraging further movement of mariculture activities into open waters. In many countries with well-developed mariculture industries, there is frequently increasing concern about environmental carrying capacity and associated issues, such as disease and stock escapes (Tacon and Halwart, 2007). There is also growing conflict between mariculture and other users of coastal waters in situations where there has been rapid expansion of coastal aquaculture. In many parts of the world, a number of well-organized non-governmental organization (NGO) groups have also been effective in influencing public opinion against the proliferation of mariculture in coastal waters. As a result, it has become increasingly difficult in many nations to secure new growing space for mariculture in coastal waters. Moving mariculture into more open waters, further from the coast, is one means to avoid these issues.

Driving the need for increased mariculture production is the continuing growth in global market demand for seafood products, which is a result of an increasing global population and increasing per capita fish consumption despite the more or less static production from capture fisheries. Aquaculture production has been responding to this increasing global demand in a number of ways, not only by increasing production. Up until the last decade, much of the aquaculture production focus has been on higher value species such as shrimp, cod, salmon, bass and seabream, which have all had strong increases in production (FAO, 2009). This has been due to the commercial opportunities to increase returns through economies of scale in production and supply, and to build on the existing market recognition of these aquaculture products. Some lower value aquaculture products, such as mussels, have also continued to increase in production to meet demand. However, in the last decade some relatively low-value aquaculture species, such as catfish and tilapia, have shown dramatic increases in production and trading (FAO, 2009). Interestingly, these species are entering and finding rapid acceptance in new markets, where they were previously virtually unknown. This is because they are meeting consumer needs for moderately-priced white fleshed fish that is distributed through supermarkets and food service channels.

Consumers are also increasingly looking for reassurance on production characteristics for aquaculture products, especially food and environmental safety (FAO, 2009). Ultimately, this may benefit offshore mariculture production as it has the potential to be seen by consumers as more environmentally sound than coastal mariculture production methods. Consumers of aquaculture products are also increasingly demanding convenience, palatability and a diversity of product offerings largely due to urbanization, increasing affluence and the reduced time people have available for food preparation (FAO, 2009). As a consequence, there has been an increasing amount of value-adding in aquaculture products. Previously, aquaculture products, such as farm-raised salmon, were more usually sold fresh to attempt to attract premium prices, but they are now increasingly being processed into value-added products (Tveterås and Kvaløy, 2006). More than 90 percent of the international trade in fish and fisheries products is now in processed forms, while 10 percent is live, fresh or chilled. Exports of frozen fish have been increasing, from 31 percent of the total quantity of fish exports in 1996 to 39 percent in 2006.

There have also been enormous recent changes in seafood value chains, with the rise of supermarkets and chains of food service outlets as the increasingly dominant consumer outlets for seafood (FAO, 2009; Tveterås and Kvaløy, 2006). These have become major influences on aquaculture production as they are demanding reduced pricing, increased coordination of their suppliers, greater supply volumes, more product differentiation, and assurances of food and environmental safety (Tveterås and Kvaløy, 2006). These forces have driven rapid vertical and horizontal integration among many aquaculture producers. Furthermore, the desire to increase efficiency has seen moves to decrease the labour costs in aquaculture production, by replacing manual tasks with mechanization, or the increasing use of sources of low-cost labour, especially in developing countries, such as in parts of Asia (FAO, 2009; Tveterås and Kvaløy, 2006). For example, the People's Republic of China has recently emerged as the largest trader of seafood products in the world due to its extensive importing, processing, and re-export of seafood products from around the world. Developing countries now provide over half of the fishery products entering into international commercial trade (Möller, 2003). These countries have acquired the expertise and processing technology, as well as satisfying the stringent safety and quality requirements of demanding affluent markets, especially in Europe and the United States of America. They are well placed to connect with more local sources of aquaculture supply, if they can be developed, such as from mariculture in open waters.

There has also been a recent trend to move more aquaculture production to low-labour cost countries, which also often have fewer regulatory constraints on aquaculture development (FAO, 2009; OECD, 2010). Many of these developing countries, such as the Republic of the Philippines, the Kingdom of Thailand and the Socialist Republic of Viet Nam, are within the tropical zone. Much of this mariculture production has initially been undertaken by small-scale family farming units using simple technology and most often in shallow coastal waters, often known as artisanal aquaculture (OECD, 2010). This situation is changing rapidly with the introduction and growth of larger-scale commercial production by corporate entities that are introducing advanced aquaculture technology, often with foreign expertise and investment. In many developing nations this trend for attracting foreign aquaculture investment and expertise is being actively encouraged with significant financial incentives by governments. For mariculture in the tropical zone this is significant because there are relatively few existing species that have the capacity to be immediately transferred into large-scale open ocean aquaculture, building from an assured base of well-developed commercial production in inshore waters. The application and development of new aquaculture technology appears to have been holding back the rapid expansion in the tropical zone for emerging commercial finfish species, such as cobia, Asian seabass (barramundi; *Lates calcarifer*), and a range of tropical grouper and snapper species (FAO, 2009). However, there are signs that this is changing with some recent significant commercial mariculture developments in developing countries.

To become commercially established, the expansion of aquaculture output from these species needs to be able to rapidly capture a larger share of the global market (FAO, 2009). This can be achieved by substituting products already on the market, especially through price competitiveness. However, the ability to maintain substantially lower prices than competitors usually requires culture technology improvements, faster or more efficient growing species compared with those generally used in the industry, and larger scale production. Therefore, aquaculturalists have to overcome biological and technology hurdles to create new production cost advantages, such as from integrated hatcheries, on-growing facilities and economies of scale in input procurement and growout. For widespread commercial uptake of open water mariculture, the technology must provide sufficient financial advantages to make the product competitive in the marketplace, while also providing sufficient financial return to offset the additional capital cost and operating cost for this open water mariculture technology. This is a significant challenge for the wider introduction of offshore mariculture technology, when there appears to be capacity to further expand coastal and off-the-coast mariculture, especially in the tropical zone. This expansion has already begun to occur rapidly in recent years for finfish species in countries such as China, the Republic of Korea and the Philippines (Chen *et al.*, 2007; Chen *et al.*, 2008; De Silva and Phillips, 2007). Further mariculture development potential is readily available in other tropical regions of the world, especially Asia, but is constrained by a lack of political, financial and physical infrastructure, as well as a shortage of available aquaculture expertise and capital.

Concerns about climate change and global energy supplies may in the future have an impact on more energy-intensive forms of aquaculture production (FAO, 2009). It is likely that mariculture in open waters will prove to be more energy intensive due to the transit distances involved in servicing farms, however, improvements in automation may reduce energy-intensity of this form of production. Remote automation appears to be a current focus for development activities for offshore mariculture (Browdy and Hargreaves, 2009). Future increases in energy prices may also favour increasing aquaculture production in developing countries which have less substitution of labour with more energy-intensive mechanization. This is unlikely to be offset by the distance from market as transport costs are typically only a small component of the price of final consumer-ready aquaculture products (FAO, 2009).

Off-the-coast and offshore mariculture technology

There is a small amount of published information on offshore seaweed farming, but it is not an area that has attracted a great deal of research or commercial attention (Buck and Buchholz, 2004) at the global level.

Off-the-coast commercial shellfish mariculture has been occurring in a number of locations as an extension of existing shellfish farming in more sheltered waters (New Zealand Ministry of Fisheries, 2009). Typically, these activities are in large embayments where some degree of shelter is already provided rather than in more open waters. The same farming methods as are used in more sheltered waters are normally used (e.g. Japanese long-line system for mussels), but often with the use of heavier gear, including larger floats, anchors and mooring lines to cope with the additional stresses of greater wave and wind exposure (Fredheim and Lien, 2003; Jeffs *et al.*, 1999; Jenkins, 1985; Johns and Hickman, 1985; Lien and Fredheim, 2003). However, using this technology for shellfish mariculture in more open waters is problematic because of greatly increased strain loads on farm infrastructure, especially between floats on the backbone lines during large wave conditions (Merino, 1997). Increased vertical movement in the farming structure due to wave motion can also result in the detachment of farm stock such as for mussels which rely on byssus thread attachment to the farming structure. Offshore mariculture of shellfish has been undertaken on an experimental scale at a number of locations in temperate regions where large-scale commercial shellfish farming is more prevalent (Bonardelli and Levesque, 1997; Chambers *et al.*, 2003; Langan, 2000a; 2000b). These have concentrated on submerging traditional suspended longline and pearl net culture systems to depths of 20 m below the sea surface to avoid the difficulties of retaining surface floats in exposed open waters, but with stronger mooring systems. This approach has worked well and survived the effects of high winds (100 km h^{-1}) and seas generated by a hurricane, as well as wave heights in excess of 6 m (Langan, 2000a; Paul, 2000). However, some difficulties were encountered in maintaining the correct headline depth as the mussel stock grew and added increased weight to the submerged floats. As a result, some floats collapsed due to the increased water pressure from being pulled to greater water depths. (Chambers *et al.*, 2003). Besides the failure of floats, some problems have also been encountered in offshore shellfish farms with fouling and predation by sea stars (Chambers *et al.*, 2003; Hampson *et al.*, 1999).

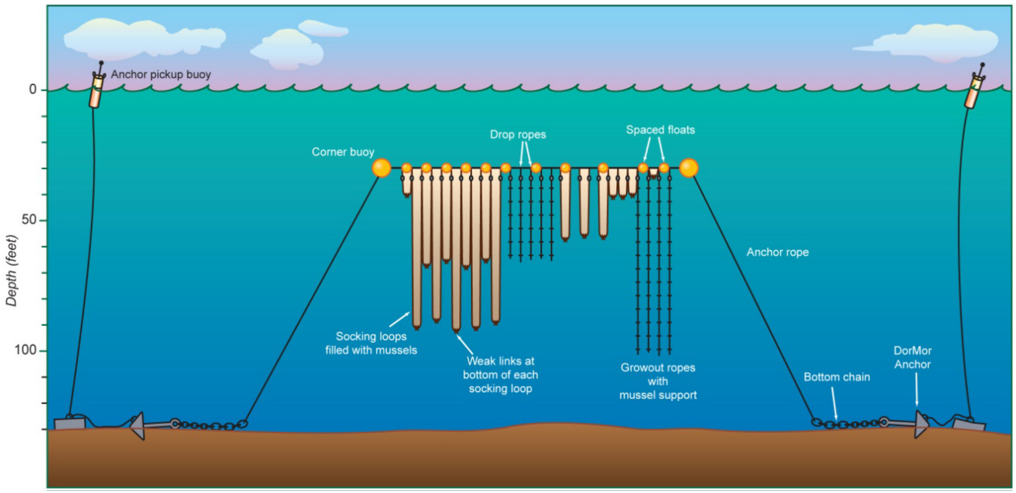
There are currently, several commercial producers using the offshore shellfish farming technology developed by the University of New Hampshire, on a relatively small-scale (R. Langan, personal communication, 2009) (Figure 2). One farm is operating around 1.2 km off the coast of California and has about 15 working longlines, each producing around 10 tonnes of blue mussels (*Mytilus galloprovincialis*) per line with a 6–8 month production cycle (www.sbmariculture.com). The company is also exploring the culture of Pacific oysters and rock scallops. Another commercial operation is off the coast of New Hampshire, and while there is a longline capacity to produce 90–100 tonnes annually, the operator has not come close to full utilization of the gear for a number of logistic reasons. Two further initial farms have recently been set up off the coast of Massachusetts, and if they show initial commercial success they will look at further expansion. There is reportedly another commercial-scale shellfish farm using the offshore farming technology in the Black Sea in the Republic of Turkey, but details of their location and production are sketchy.

Interestingly, these initial commercial efforts at commercializing offshore shellfish mariculture methods developed by the University of New Hampshire at a site 10 km (52 m depth) offshore have been located closer to the coast and in shallower water; New Hampshire commercial farm site (4.5 km and 35–40 m), California commercial site (1.2 km and 45 m), Martha's Vineyard, Massachusetts sites (3 km and 26 m) and (4 km and 32 m), Rhode Island sites (4 km and 25 m) and (6 km and 38 m) (R. Langan, personal communication, 2009). This trend is in line with economic modelling which predict that distance offshore is an important factor for determining the major operating costs of an offshore mariculture operation (Kite-Powell *et al.*, 2003b).

Off-the-coast sea cage farming of a variety of finfish species has been occurring for many years based on designs that were the result of incremental development of floating sea cages traditionally used in coastal waters. Floating sea cage designs made of plastic (high density polyethylene) for culturing finfish were first made by Polarcirkel in the Kingdom of Norway in 1974 and this style of plastic cage is now widely used around the world for mariculture in both coastal waters and off-the-coast situations (www.akvasmart.com; www.aqualine.no) (Svensson, 1993). Floating sea cage systems made of flexible rubber have also been important in the development of off-the-coast

FIGURE 2

Submerged longline system for offshore mariculture of shellfish, such as mussels and scallops



Source: Hoagland, Kite-Powell and Jin, 2003 – Illustration by Jack Cook, Woods Hole Oceanographic Institution.

sea cage farming (Gunnarsson, 1993). The first rubber sea cage systems fitted with plastic collar rings (Bridgestone Hi-Seas fish cages; Gunnarsson, 1993) were first used in Japan in the early 1980s and then their use spread around the world. These floating plastic and rubber cage systems increased in size from earlier designs used in shallow water, increasing from 10 m to 20 m hexagonal cages and the depth of the nets that were held beneath them also increased from 10 m to 30 m depth. Subsequent research has found that larger sea cages tend to result in faster growth of fish (20–30 percent in some instances), better feed conversion, lower mortality and better quality fish (Chen *et al.*, 2008; Guldberg *et al.*, 1993). These are important findings for considering further increases in the size of culture systems. During the 1980s there was substantial development work undertaken on floating sea cage designs in response to increasing demand from the mariculture industry to be able to operate sea cages in more open waters (i.e. significant wave height to 4 m or surviving waves of 7 m once in 30 years) and the ability for sea cages to be towed from one location to another to allow culture areas to be fallowed (Svensson, 1993). The efforts resulted in more integrated floating sea cage farming systems, including base platforms for feeding and managing groups of sea cages and advanced mooring systems and floating structures that were capable of withstanding more extreme weather conditions. These more robust systems were also able to withstand the stress of being handled with large servicing vessels of 30–40 m in length, such as pulling alongside cages in high seas. Since this time, further remote operational technology has been developed for offshore sea cage farming situations, including for monitoring fish, managing feeding, as well as providing security from large marine predators and theft (Davis *et al.*, 1993; Dunn and Dalland, 1993; Jackman and Ace-Hopkins, 1993).

Typically, all of these sea cage designs utilized a floating frame that supports the net pen and usually have frames made of steel walkways connected by hinges, floating sections of rubber hose or sections of floating plastic pipe (Beveridge, 2004). The floating cage is held in position by one or more anchors and weights are used to hold down the net pen in the water column. These cages are sufficiently flexible to ride out the wave loadings in sheltered or semi-sheltered situations where smaller and shorter period waves are the norm (Beveridge, 2004). However, in fully exposed open water situations, the greater wave periods and wave heights place extreme forces that are generally beyond the operational limits of conventional floating sea cage designs

FIGURE 3
Farmocean offshore system – semi-submerged offshore sea cage system for offshore mariculture of finfish

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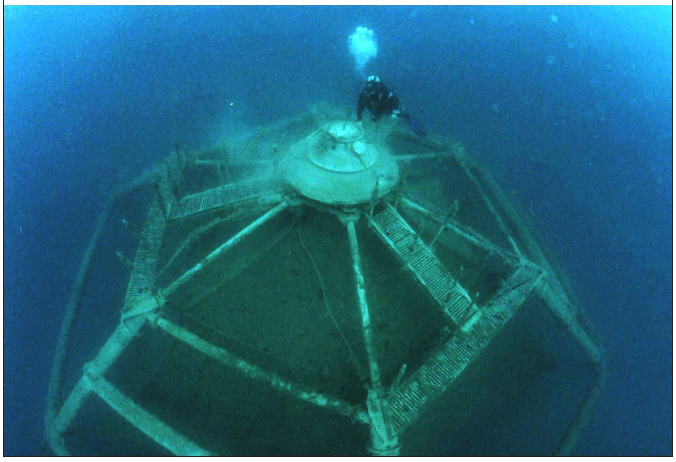
and materials (Loverich and Croker, 1993). The wave motion causes flexing of the floating frame and deforms the net pen effectively reducing the area available for fish culture within the pen by up to 80 percent because the fish need to remain within a volume where the wave particles do not pass through the net pen mesh (Lien, 1993). As a result, a very wide range of designs and concepts have been promoted for offshore mariculture (Beveridge, 2004). A large number of these evolved from offshore oil and gas engineering designs, and some have promoted the use of modified petroleum infrastructure that is no longer in use (Hanson, 1974a; 1974b; Ribakoff, Rothwell and Hanson, 1974; Stickney, 1997). This included bottom-supported platforms, such as Texas towers, jack-up rigs, and monopods, as well as floating and semi-submersible platforms, including modified conventional ships and barges, as well as net pens supported between moored spar bouys.

A frequent approach to overcoming the problem of wave stresses on offshore mariculture infrastructure is to enclose and submerge the infrastructure either permanently or during periods of adverse weather. This results in decreased stress on the infrastructure because water particle motion due to the waves in the sea decreases exponentially from the surface and is reduced to zero at a depth corresponding to half the wave length (Beveridge, 2004). Submerging sea cages also has potential advantages in avoiding conflict with some other water users, such as boat traffic. It can also help in avoiding surface jellyfish swarms and damage from collisions with floating debris (Beveridge, 2004; Ryan, Jackson and Maguire, 2007). Submerged cages tend to be more difficult to operate and cause problems for the culture of some species. For example, submerged cages are thought to cause problems for swim bladder physiology of some fish species, such as salmon which have an open duct between the oesophagus and the atmosphere and need access to the atmosphere in order to fill the swim bladder with air (Rubach and Svendsen, 1993).

Offshore sea cages of a wide variety of designs have been devised, built, tested and commercialized to some extent over the past 30 years or more (Beveridge, 2004). It would appear that some submerged and semi-submerged sea cage designs are beginning to emerge as the most likely types to be commercialized more widely.

Semi-submersible Farmocean sea cages (Figure 3) were designed in the Kingdom of Sweden and first used in 1986 and are now widely used, especially in Europe and the Mediterranean (Beveridge, 2004; Scott and Muir, 2000). They consist of a semi-submersible steel ring and cone pontoon, topped by a feed silo and computer control centre. Parts of the ring can be flooded to provide ballast and semi-submerge the structure. Beneath the metal cone a sea cage is suspended and held down by weights at its base and the internal volume of the sea cage can vary in size from 2 500 to 6 000 m^3. The conical pontoon is moored to the seafloor from the outer circular pontoon. These seacages are capable of containing up to 150 tonnes of fish and withstanding waves of over 5 m in height.

FIGURE 4
Sadco-Shelf sea cage – submerged offshore sea cage system for offshore mariculture of finfish



COURTESY OF LEONID BUGROV

Another offshore sea cage design that has been used in Europe and the Mediterranean is the Refa sea cage which is a semi-submersible tension leg design (Beveridge, 2004; James and Slaski, 2006; Scott and Muir, 2000). The sea cages are moored to the seafloor directly beneath the sea cage so that under extreme conditions they are designed to submerge of their own accord (www.refamed.com). A plastic frame is used to provide buoyancy at the surface and to form the circular shape of the enclosed net pen which ranges in size from 10 to 20 m in diameter and 800–12 000 m^3 in volume and is capable of holding up to 300 tonnes of fish at a high stocking density. Concerns have been raised regarding the mooring arrangements and deformation of the net pen when this design of sea cage is under load (Ágústsson, 2004).

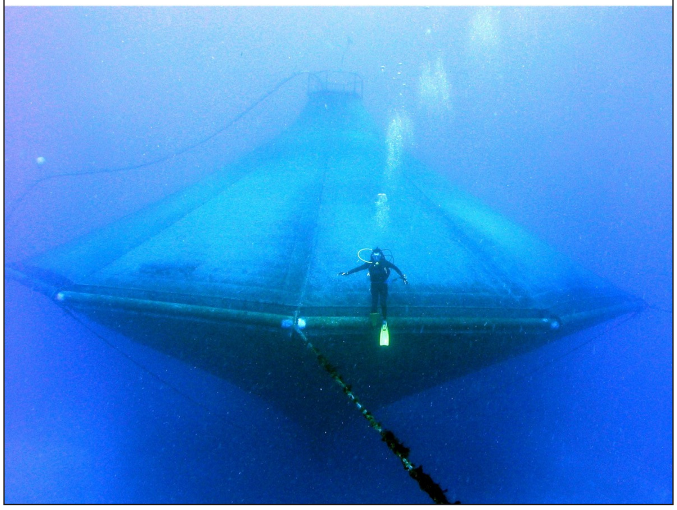
Sadco-Shelf is a rigid hexagonal cage design constructed of tubular steel that is fully submersible (www.sadco-shelf.sp.ru) (Ágústsson, 2004; Beveridge, 2004) (Figure 4). In the submerged position the sea cage is reported to be able to withstand waves over 15 m in height and current speeds in excess of 1.5 m s^{-1}. The Sadco 2000 model has a sea cage that is 16 m in diameter and has a volume of 2 000 m^3 that is capable of producing 80 tonnes of finfish. The design includes a 2 000 litre submersible fish feed reservoir with automated feeding. Sadco sea cages have been deployed in the Caspian, Black and Mediterranean Seas.

Other submersible rigid sea cage designs include the Trident and MII (Marine Industries and Investments) sea cages, however, there appears to be relatively little recent information on their use suggesting they have not found favour with researchers and potential commercial users (Ágústsson, 2004; James and Slaski, 2006; Scott and Muir, 2000). The Trident cage is reported to have withstood breaking waves of over 3.5 m in height and wind speeds of over 100 km h^{-1} while partially submerged.

The designs of submersible open ocean sea cages that have been most widely used, especially in the tropical zone, are Ocean Spar designs (www.oceanspar.com, www.snapperfarm.com) (Baldwin *et al.*, 2000; Halwart, Soto and Arthur, 2007; James and Slaski, 2006). Ocean Spar sea cages have been used in Hawaii (USA), Puerto Rico, Bahamas, Gulf of Mexico, Cyprus and New Hampshire (USA). These sea cages consist of a central hollow steel spar that is used to control buoyancy that is surrounded by a ring made of pipe steel of 20 m or more in diameter that is used as a frame for holding the net pen. The submersible sea cage can be brought to the surface through altering the buoyancy of the cage structure. The sea cage has a volume of 3 000 m^3 and there is the potential to build larger units. The cages have withstood extreme weather conditions, including hurricane winds of over 100 km h^{-1} for almost 24 hours in the Bahamas with no damage to the submerged cage or the contained fish (Benetti, 2004). The cage has also survived waves in excess of 5 m height on the eastern part of the United States of America and the design has been modelled to withstand waves up to 9 m (Ágústsson, 2004). The difficulties reported with operating this sea cage system relate to the initial high capital cost, the requirement for costly diver servicing of the cage, shark damage to netting and the need for a more efficient feeding system (Ágústsson, 2004; Halwart, Soto and Arthur, 2007; James and Slaski, 2006; Scott and Muir, 2000).

Several submersible sea cage designs have been developed in China and Taiwan Province of China, including the PDW and SLW designs in China (Chen *et al.*,

FIGURE 5
Ocean Spar SeaStation 3000 sea cage submerged in the blue waters off Cape Eleuthera in the Bahamas



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2007; Chen *et al.*, 2008; De Silva and Phillips, 2007; Guo and Tao, 2004; Xu, 2004). The PDW designs are especially designed for farming flatfish and have multiple layers to facilitate the bottom dwelling behaviour of the cultured flat fish. An experimental PDW sea cage survived typhoon winds over 90 km h^{-1} and waves of over 5 m in height.

Economics

The operation for many years of off-the-coast mariculture for fish and shellfish in many parts of the world would tend to confirm that this activity can be financially viable for some species in some locations using existing technology. However, globally, the commercialization of offshore mariculture technology is still emerging and the application of the technology on a commercial-scale is still relatively small, but increasing in recent years consistent with improving prospects for establishing consistent commercial viability (Halwart, Soto and Arthur, 2007; James and Slaski, 2006). The vast majority of this activity relates to finfish farming and much of it is being conducted in the tropical zone because of faster growth of fish due to higher water temperatures, as well as more favourable operating conditions, e.g. more flexible regulatory regimes, better water clarity, more consistent and favourable weather conditions.

One of the major delaying factors for progressing open ocean mariculture of finfish in tropical regions has been the absence of existing and well-established commercial mariculture of finfish species that would be suitable for offshore mariculture systems. Consequently, the development of offshore farming technology has had to contend with the development of mariculture techniques for largely unknown aquaculture species, simultaneously with developing new farming technology. This contrasts significantly with the development of off-the-coast mariculture mostly in temperate waters which has largely consisted of advancing mariculture infrastructure for existing aquaculture species for which the husbandry and commercial culture capabilities are well known from prior inshore mariculture experience. For temperate waters, where there is extensive commercial aquaculture of species, such as salmonids, there has been somewhat limited commercial appetite to move into offshore farming. This limited interest perhaps relates to the availability of existing coastal space for mariculture expansion and the opportunities for working to improve commercial returns from existing aquaculture operations through less risky and capital intensive developments, such as improving husbandry and feed formulation and delivery.

A number of published studies have been undertaken to investigate the economic viability of open ocean mariculture operations, for both shellfish and finfish, with conflicting results.

Economic modelling has suggested that open ocean mariculture of two species of shellfish, sea scallops (*Placopecten magellanicus*) and the blue mussel (*Mytilus edulis*), has the potential to be economically viable in temperate New England waters (Hoagland, Kite-Powell and Jin, 2003; Kite-Powell, Hoagland and Jin, 2003a; Kite-Powell *et al.*, 2003b). The study concluded that seabed seeding appeared to be the most promising approach for scallop culture as the costs of buying, maintaining, deploying and harvesting open water scallop growing structures was too expensive.

The modelling, that was based on growth data from experimentally grown mussels in offshore waters, predicted that commercial mussel culture using submerged longlines was potentially economically viable, provided a sufficiently high market price could be maintained. However, the risks of crop loss due to fouling and extreme weather posed a significant business risk. It was suggested that this risk might be overcome through the diversification of species (i.e. including sea bed enhancement of scallops) and this would also help to support the cost of the equipment required for servicing the offshore farm, such as vessels. The establishment of a farm required significant initial capital investment (>USD 1 million) with projections of positive cash flow first occurring three to seven years out depending on the landing prices for the cultured shellfish (Hoagland, Kite-Powell and Jin, 2003; Kite-Powell, Hoagland and Jin, 2003a).

Another study of the economic viability of longline farming of mussels in the offshore waters of Canada concluded that it was not economically viable, due in a large part to the slow growth of the shellfish in the cold waters (Bonardelli and Levesque, 1997). Economic analyses undertaken by privately owned mariculture companies in New Zealand has indicated that offshore mussel farming was likely to be marginal at best, despite New Zealand operating some of the most efficient large-scale mussel farming systems in the world and attracting a premium price in the market for the endemic mussel species (*Perna canaliculus*) (J. Wilson, personal communication, 2009). Regardless of the less than optimist economic projections, a number of commercial shellfish farms have emerged that are utilizing the offshore farming technology developed in New Hampshire (R. Langan, personal communication, 2009). However, despite extensive information searching, no examples of offshore shellfish mariculture could be found for the tropical zone.

A number of economic modelling studies have also been conducted for offshore finfish farming operations. An economic model was developed for a large-scale offshore sea cage finfish operation in the Gulf of Mexico (Posadas and Bridger, 2003). The model considered three potential finfish species for which growth and culture density data were available; cobia (*Rachycentron canadum*), red snapper (*Lutjanus campechanus*) and red drum (*Sciaenops ocellatus*). The modelling indicated that offshore mariculture of all three species were unlikely to be economically viable unless the scale of the farm was increased, landed prices were increased by at least USD1 kg^{-1} and stocking densities were very high. Cobia was the species that showed the greatest potential for reaching commercial viability.

An economic model was developed for a finfish mariculture operation in the open ocean off New England that was growing cod, salmon and flounder (Kite-Powell *et al.*, 2003b). The model suggested it would be economically viable and indicated the importance of parameters such as, the distance from shore to the farm site, feed cost and maximum stocking density, in determining commercial viability. The model also indicated that significant costs were associated with operating and maintaining the cage system, vessels, as well as staffing, emphasizing the importance of greater automation for operating open ocean farming systems.

An economic model was used to evaluate the potential for the production of gilthead seabream in floating off-the-coast cages in the Canary Islands and the Mediterranean, an activity that already occurs in the Mediterranean (Gasca-Leyva, León and Hernández, 2003a; 2003b; Gasca-Leyva *et al.*, 2002; 2003c). The modelling found that differences in the growth rates of fish due to differences in water temperature at different sites could be offset by harvesting at different sizes to meet differences in market preference. Variable costs, such as feed and labour, made up around 50 percent of total costs, whereas fixed costs were a smaller overall proportion of total costs (around 13 percent) making it more difficult to generate improved financial performance based on increasing the scale of production. Regardless, the most economic scale was predicted to be a large farm in the order of 48 000 m^3. Economic sensitivity analyses indicated financial returns were unexpectedly more sensitive to changes in the level of mortality and feed use than to all other variables, except for the commercial price for final product.

An economic model for mutton snapper production in an open ocean style sea cage system (Ocean Spar Technologies LLC – Ocean Spar SeaStation) in Puerto Rico concluded that the operation could be profitable provided the scale of production was increased significantly to reduce labour costs, and the cost of the farming technology was lower (Brown *et al.*, 2002).

An economic model for an open water Atlantic salmon farming operation producing 10 000 tonnes per annum indicated it would be economically viable (Ryan, 2004), although this conclusion has subsequently been questioned (James and Slaski, 2006).

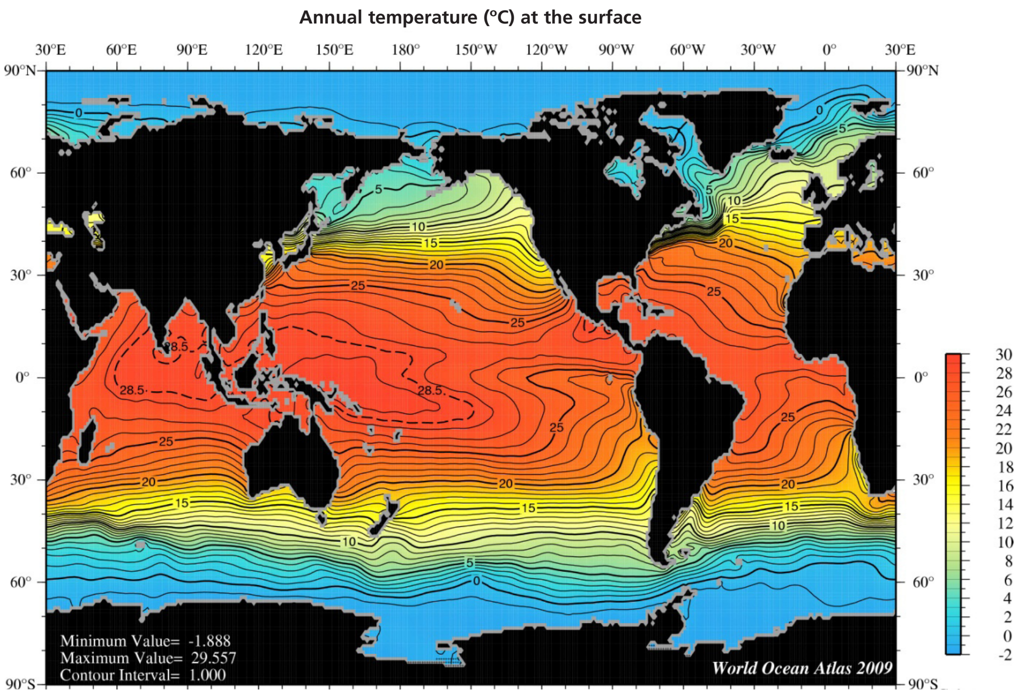
Despite the uncertain economic predictions from modelling studies, a number of commercial or pilot scale open water finfish farming projects have progressed in the tropical zone during last decade, and new initiatives are developing. Experimental and commercial farms have been operated in Hawaii, Bahamas, Puerto Rico, Gulf of Mexico and further open water farms have been proposed or are under development in St Kitts, Panama and Belize (www.marinefarmsbelize.com) (O'Hanlon *et al.,* 2003).

THE GROWING ENVIRONMENT

As might be expected, the world's oceans in the tropical zone generally have warmer surface waters than oceans in higher latitudes (Locarnini *et al.*, 2006) (Figure 6). Average annual sea surface temperatures within this tropical zone typically range between 24 and 31 °C.

Furthermore, the annual seasonal variation in sea surface temperature tends to be smaller for oceans within the tropical zone (typically a 1–2 °C range) than oceans in cooler regions of the world (typically a 5–10 °C range at latitude of 40°) (Levitus, 1987) (Figures 7 and 8). Nearer to the coast, larger annual variations in sea surface temperatures occur, typically 10–20 °C in sheltered waters. Diurnal variations in

FIGURE 6
Mean annual sea surface temperature (°C) of the world's oceans

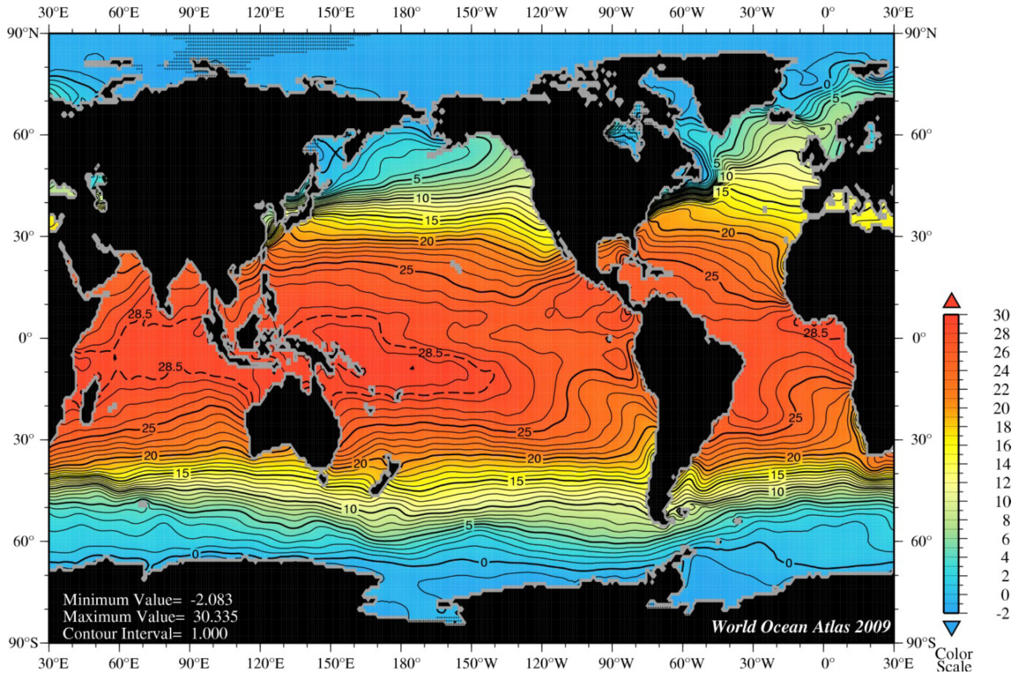


Source: World Ocean Atlas 2009 – National Oceanographic Data Center, www.nodc.noaa.gov

water temperature also tend to be higher in sheltered and shallow coastal waters where a range of 2–3 °C is common and variations of 3–4 °C have been observed (Levitus, 1987). In comparison, offshore waters typically have a diurnal range of around 1 °C.

FIGURE 7
Mean sea surface temperature (°C) of the world's oceans during winter (January–March)

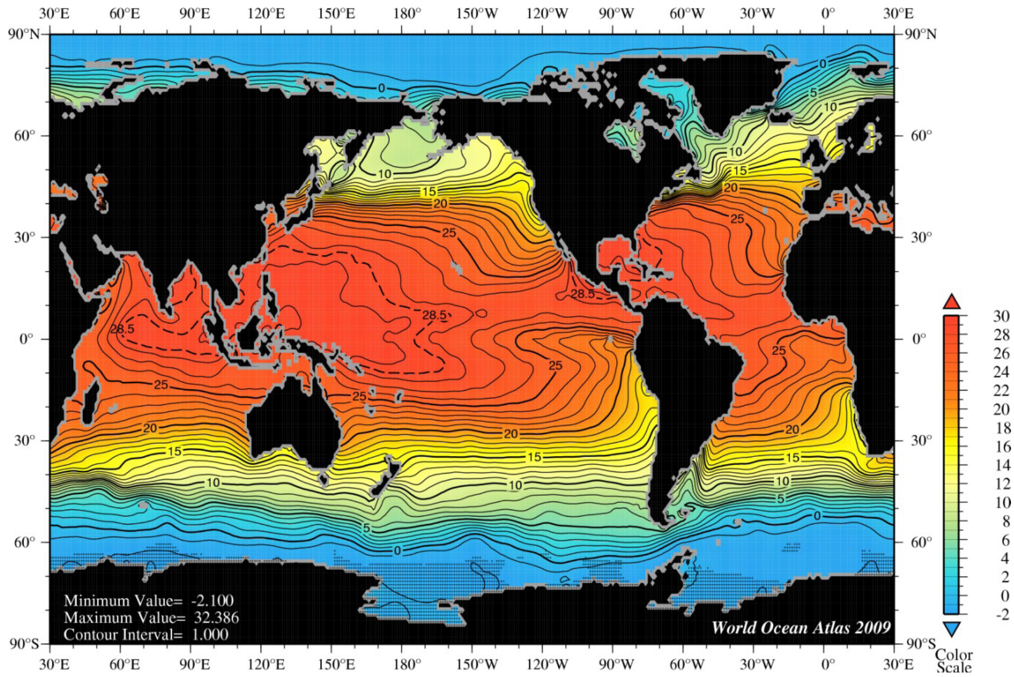
Winter (Jan.–Mar.) temperature (°C) at the surface



Source: World Ocean Atlas 2009 – National Oceanographic Data Center, www.nodc.noaa.gov

FIGURE 8
Mean sea surface temperature (°C) of the world's oceans during summer (July–September)

Summer (Jul.–Sep.) temperature (°C) at the surface



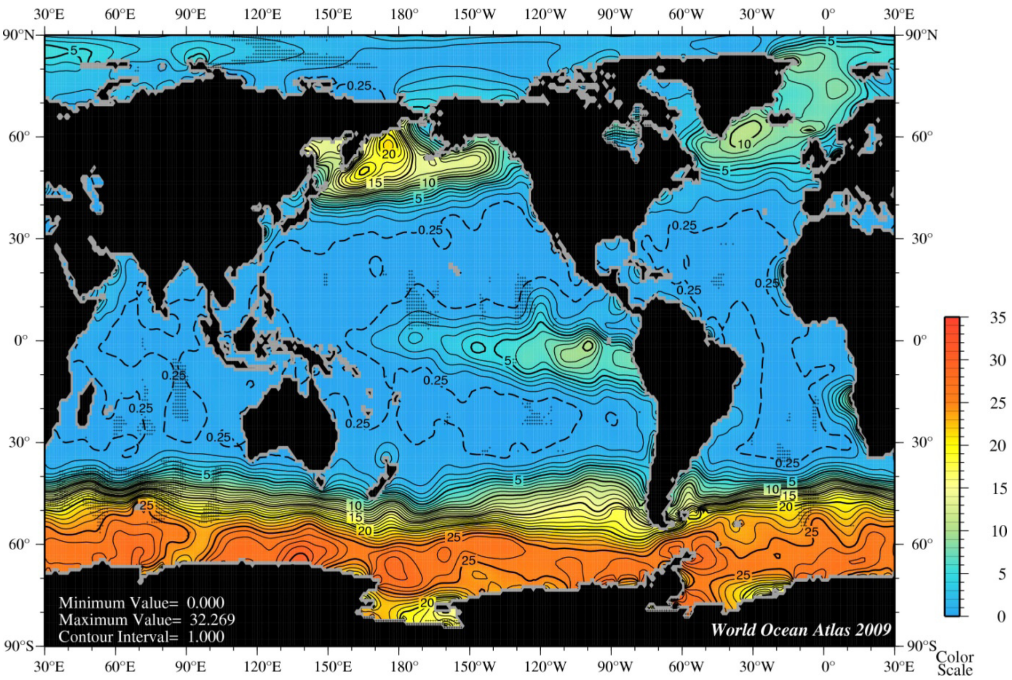
Source: World Ocean Atlas 2009 – National Oceanographic Data Center, www.nodc.noaa.gov

The maintenance of a stable temperature regime at a mariculture location can assist in improving production, especially if the ambient temperature remains close to the optimum for the cultured species. Short-term fluctuations in temperature can stress some aquaculture species, especially finfish, which in turn can result in reduced culture performance (Wheaton, 1993). Consequently, offshore waters in the tropical zone have the advantage of providing stable water temperatures for mariculture, especially for species with matching temperature optima. Furthermore, mariculture species are poikilotherms with metabolic processes frequently limited by temperature. For this reason, many tropical mariculture species are capable of higher growth rates than their temperate water counterparts although their rates of natural mortality tend to be higher (Charnov and Gillooly, 2004; Griffiths and Harrod, 2007; Jensen, 2001; Pauly, 1980). Although it is not altogether clear whether the higher rates of natural mortality are related entirely to differences in predatory effects, or that endogenous physiological effects of temperature may also play a role.

The world's oceans in the tropical zone are characterized by generally lower primary productivity due to the nutrients required for plant growth being limited in surface waters, especially nitrate and phosphate (Garcia *et al.*, 2006b) (Figures 9, 10, 11 and 12). Low concentrations of silicate also greatly limits the production of diatoms in tropical zone waters, with dinoflagellate photosynthesis more important for primary production in the tropical zone (Figure 11). Primary production tends to be higher in the nearshore coastal zone where nutrients are brought into the surface waters from the land and the interaction of nutrient rich seawater with the seabed or land typography. Nearshore coastal waters also tend to have higher levels of detrital material and dissolved organic matter, both of which contribute to the nutrition of filter feeding shellfish, together with microalgal primary producers (Dame, 1996). Having evolved in shallow coastal waters, bivalves are most abundant and diverse in coastal waters where there is sufficient suspended material to support their lifestyle. Therefore, the mariculture of filter feeding shellfish, such as mussels and oysters, in

FIGURE 9
Mean nitrate concentration of surface waters of the world's oceans

Annual nitrate (umol/l) at the surface

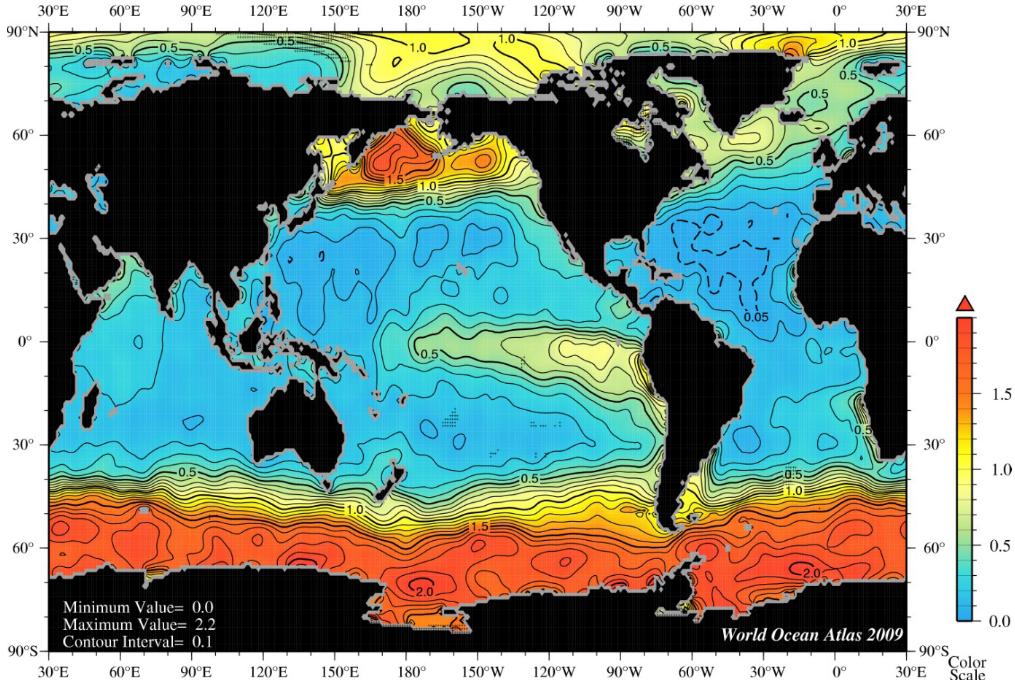


Source: World Ocean Atlas 2009 – National Oceanographic Data Center, www.nodc.noaa.gov

offshore tropical waters with low food availability is unlikely to be viable. Likewise, the culture of macroalgae in offshore tropical waters with low nutrient availability is also unlikely to be viable.

FIGURE 10
Mean phosphate concentration of surface waters of the world's oceans

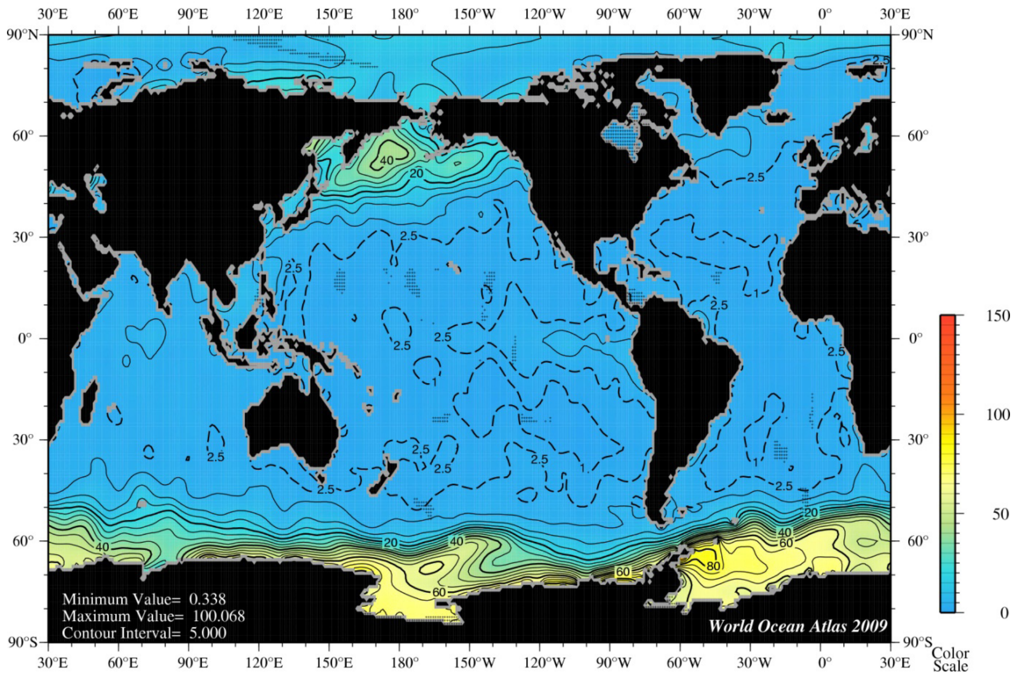
Annual phosphate (umol/l) at the surface



Source: World Ocean Atlas 2009 – National Oceanographic Data Center, www.nodc.noaa.gov

FIGURE 11
Mean silicate concentration of surface waters of the world's oceans

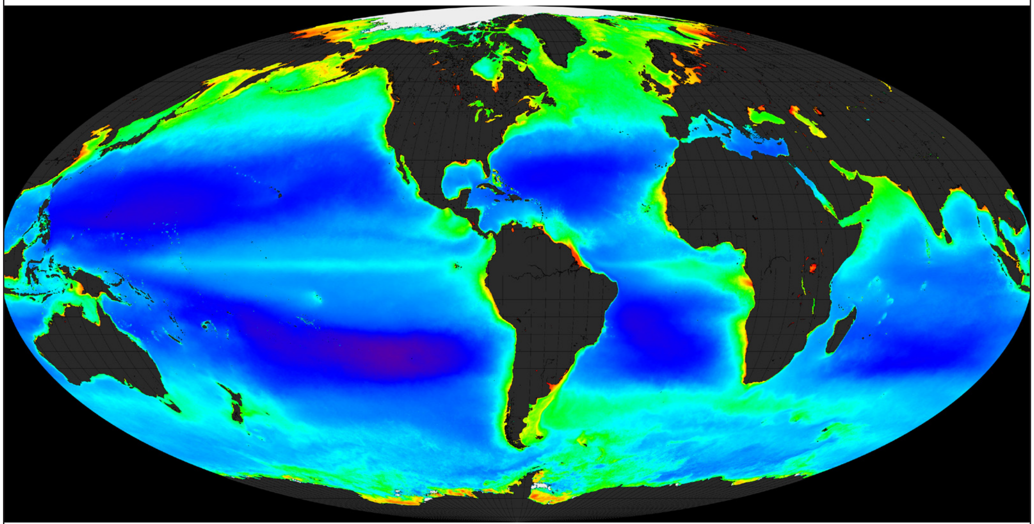
Annual silicate (umol/l) at the surface



Source: World Ocean Atlas 2009 – National Oceanographic Data Center, www.nodc.noaa.gov

FIGURE 12

Mean chlorophyll-α concentration of surface waters of the world's oceans for the period of 1997 to 2009



Source: SeaWiFs satellite data from: http://earthobservatory.nasa.gov

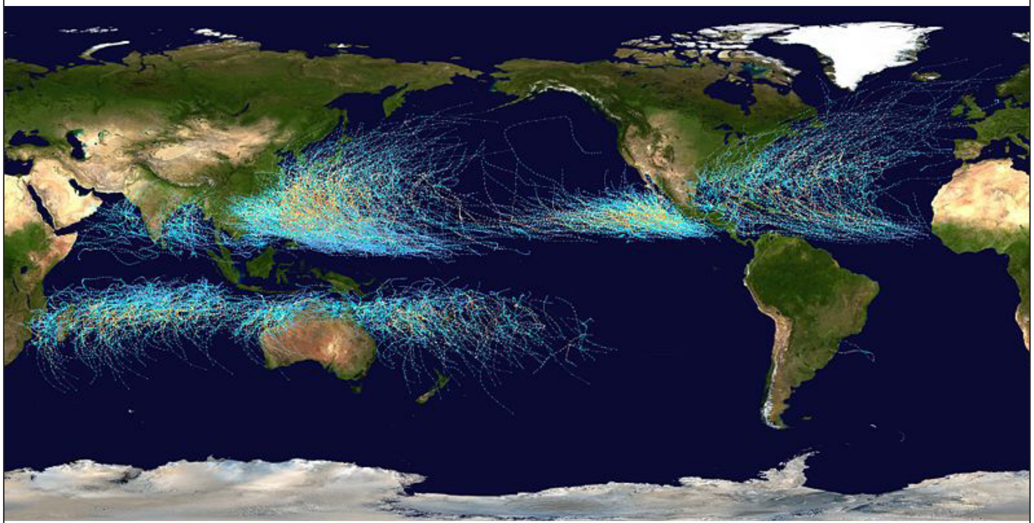
Higher nutrient levels, in particular in coastal waters, are also frequently associated with some nuisance species for mariculture activities, such as harmful algal blooms and jellyfish swarms. These nuisance events are thought to be less frequent in offshore and tropical waters with generally lower nutrients levels.

Nutrient turnover in tropical waters is significantly higher than in cooler waters at higher latitudes because of warmer water temperatures and high ambient light intensity enabling phytoplankton photosynthesis (Furnasa *et al.*, 2005). This may have important implications in terms of reducing the environmental effects of nutrient discharges from mariculture activities through their more rapid dispersal into the food chain. However, there are concerns that offshore aquaculture may result in environmental impacts through greater spread of nutrients into benthic communities that are less able to cope with high nutrient loads (O'Neill, 2007).

Coastal waters are also affected by discharges of pollutants from the land. For example, sewage discharges and water run-off from land used for farming of grazing animals releases faecal pollutants into seawater which can contaminate filter feeding shellfish in mariculture operations. This pollution risk is much reduced and resulting product quality can be improved as a result of mariculture activities being moved further from the coast (Brenner *et al.*, 2009; Stickney, 1997).

High sea surface temperatures that are 28 °C and over and are located in areas greater than 4° of latitude from the equator are the source of tropical cyclones, typhoons or hurricanes (Anthes, 1982; Chan and Shi, 1996; Nalivkin, 1983; Stow, 2004). Global climate warming is creating the sea temperature conditions conducive to the formation of tropical cyclones (Figure 13) and consequently, they appear to becoming more frequent and intense (Emanuel, 2005). These violent weather events take some time to build energy and are not officially classified as a typhoon until they generate a wind speed of more than 64 knots, although tropical storms of less than typhoon strength can form and travel in a similar fashion, and still be capable of causing considerable damage to infrastructure through flooding and high winds. Typhoons are characterized by a circling air mass and often have a diameter of influence of 500 km, with larger typhoons more than double this. Due to the rotation of the earth, tropical cyclones originating north of the equator always move in a curve to the north-west, into higher latitudes. South of the equator, typhoons always move in a curve to the west-south-west, into

FIGURE 13
Tracks of all tropical cyclones which formed worldwide from 1985 to 2005. The points show the locations of the storms at six-hourly intervals. The stronger the red hue in the tracks, the greater the wind strength for the cyclone



Source: http://en.wikipedia.org

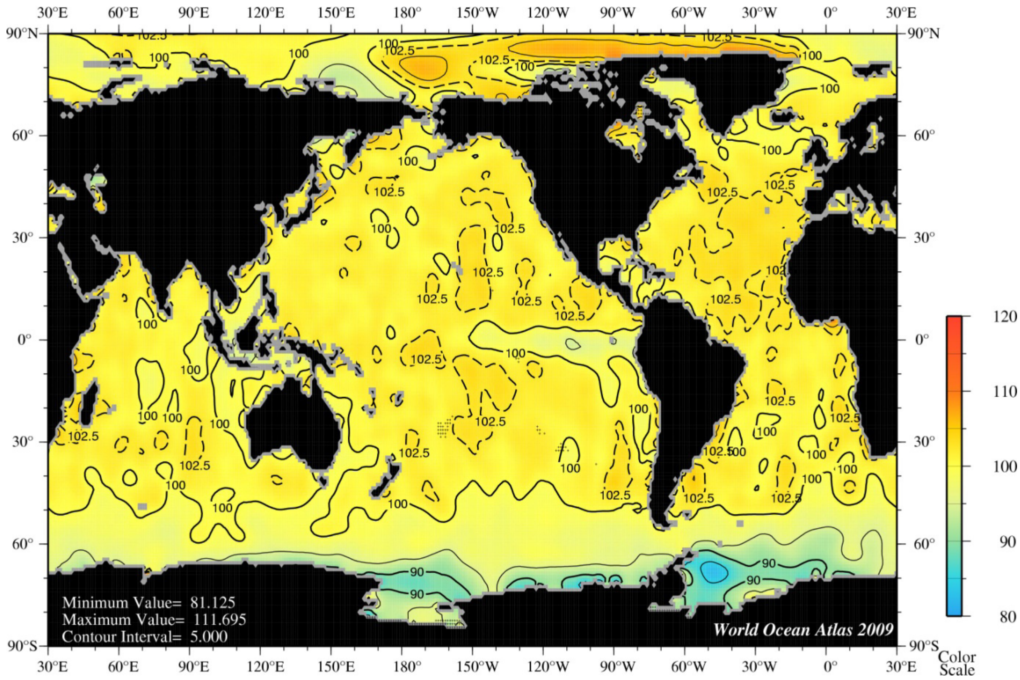
higher latitudes. Tropical cyclones represent a significant risk to mariculture operations due to the extreme winds which can create large wave conditions and for periods of up to a week or more. Such conditions are extremely challenging for retaining moored mariculture infrastructure while maintaining ongoing animal husbandry in off-the-coast and offshore locations.

In shallow coastal waters tidal movement is a dominant force for creating water currents that are vital for water exchange in mariculture. Local winds can also be important in creating movement in surface waters, but frequently coastal mariculture operations are sited in sheltered locations to avoid exposure to extreme wind and wave conditions. In the open ocean, tidal currents are relatively weak but can be important in some locations in creating mixing of deep ocean waters through the generation of internal waves (Egbert and Ray, 2000; Ross, 1995). This can lead to higher nutrient waters being brought toward the surface where they increase primary productivity. In the open ocean, local wind conditions and ocean currents are more important in generating movement of surface waters and the extent of this is variable depending on the location. Ocean currents are generated by a range of influences including water temperature, wind patterns, salinity and Earth's rotation which result in mass directed movement of ocean water. The strength of an ocean current at any location is also influenced by the interaction of the current with topographical features and other water masses. For example, ocean currents flowing between islands typically increase in speed. For off-the-coast and offshore mariculture the selection of sites with a suitable current regime is critically important to ensure sufficient water exchange, while avoiding excessive strain on moorings due to extreme current events. The presence of a continuous current of sufficient strength is particularly important for the culture of pelagic finfish at high densities in tropical waters due to their high oxygen demand and the reduced oxygen dissolution in warm seawater. Typically water currents in excess of 0.1–0.3 m s^{-1} are required in such circumstances.

While oxygen concentration in surface waters of the world's oceans are mostly in the vicinity of 100 percent, the higher sea water temperatures found in the tropical zone limits the dissolution of oxygen and carbon dioxide (Garcia *et al.*, 2006a) (Figures 14 and 15). Consequently, surface waters in the tropical zone contain significantly less dissolved oxygen than in temperate regions of the world and have a lower capacity to absorb waste carbon dioxide from aquatic animal metabolism. This is an important consideration for the offshore mariculture of pelagic finfish at high densities in tropical waters due to their high oxygen demand.

FIGURE 14
Mean annual percent oxygen saturation of surface waters of the world's oceans

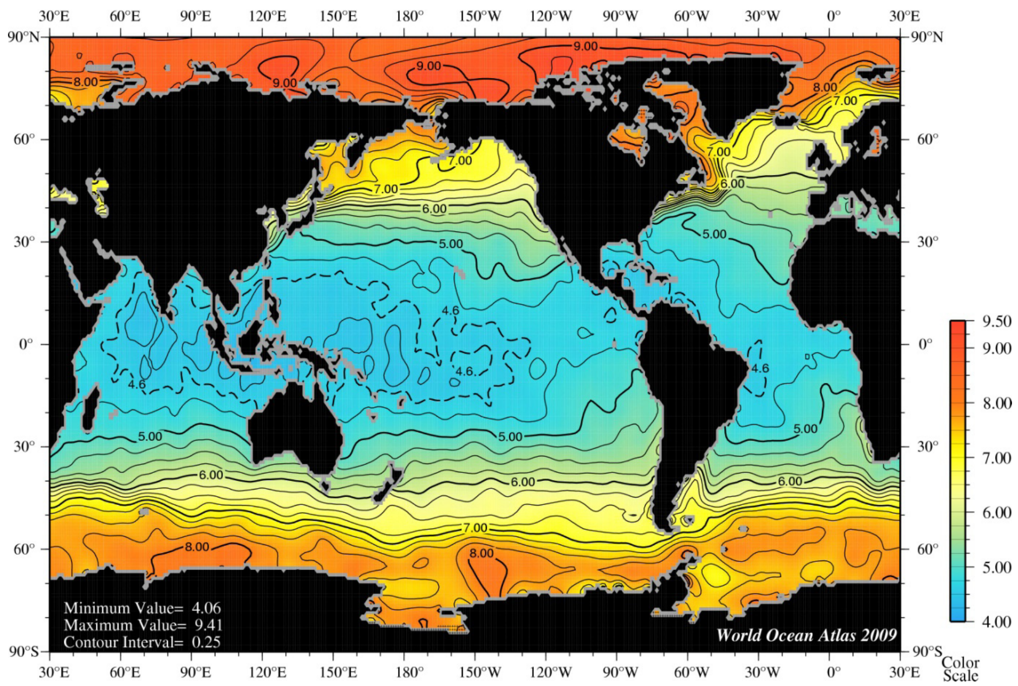
Annual percent oxygen saturation at the surface



Source: World Ocean Atlas 2009 – National Oceanographic Data Center, www.nodc.noaa.gov

FIGURE 15
Mean annual oxygen concentration of surface waters of the world's oceans

Annual oxygen (ml/l) at the surface



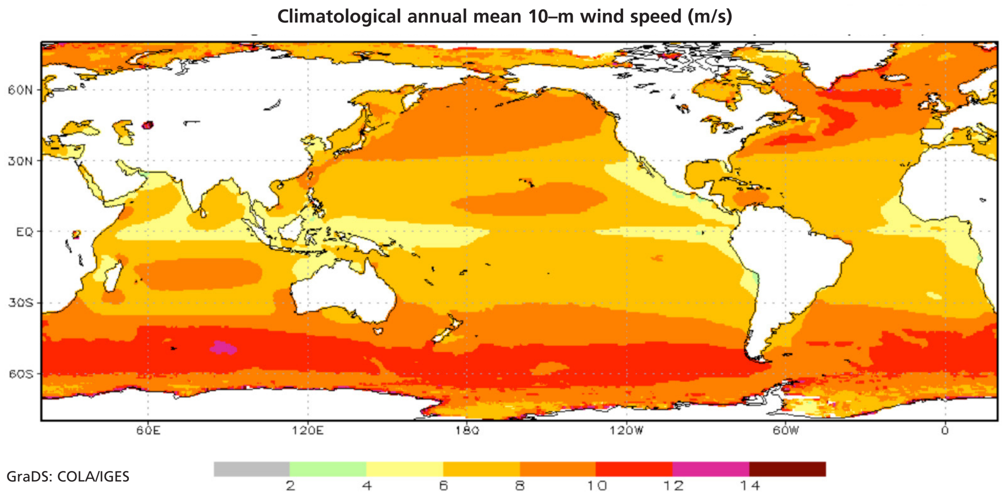
Source: World Ocean Atlas 2009 – National Oceanographic Data Center, www.nodc.noaa.gov

In general, there is less wind over the oceans of the tropical zone (Figure 16). Areas of stronger average winds are the "roaring forties" in the temperate zone of the Southern Hemisphere, the extra-tropical cyclonic activity over the Northern Atlantic and the Northern Pacific, and the Somali Jet in the Arabian Sea (Petersen *et al.*, 1997). In general, coastal waters benefit from land masses providing shelter from large-scale wind flows, but this sheltering effect is reduced with distance offshore from the coast.

Average sea surface salinity reaches its maximum values (>35 ‰) in the subtropics at about 25° North and 25° South of the equator (Figure 17), especially in areas associated with the trade winds where evaporation due to wind and warm water temperatures exceeds replacement with precipitation (Antonov *et al.*, 2006). Coastal waters tend to have lower salinity due to accumulated freshwater runoff from the land mass into adjacent coastal waters. Waters with higher salinity also have a reduced ability to retain dissolved gases, which is important for respiratory gas exchange for cultured fishes (Stirling, 1985). Although many fish and shellfish species are euryhaline (i.e. capable of surviving in a wide range of salinities) their growth is influenced by salinity because between 10 and 50 percent of their total energy budget is used in osmoregulation (Boeuf and Payan, 2001; Gosling, 2003; Saxby, 2002). Furthermore, for fish there is evidence that food intake and stimulation of food conversion are both mediated by environmental salinity, sometimes in combination with temperature (Boeuf and Payan, 2001). The reasons for this are not entirely clear, but many hormones are known to be active in both osmoregulation and growth regulation, e.g. in the control of food intake. In general, it appears that marine fish tend to have higher growth rates in moderate salinity water <30 ‰. Therefore, mariculture in high salinity water, as is more frequently encountered in offshore situations, has the potential to result in reduced growth rates for some species.

The transparency of upper ocean waters in general is higher in open oceans, especially in the tropical zone (Pickard and Emery, 1990). Water transparency generally decreases in mid and higher latitudes, as in the vicinity of most coastlines. Lower water transparency is related to the increased presence of phytoplankton and other suspended and dissolved material in coastal and temperate waters. Overall, light tends to influence fish growth through stimulating food intake and better food conversion efficiency (Boeuf and Le Bail, 1999). Reduced water transparency has the potential to reduce the efficiency of visual feeding on pellets by cultured finfish, but the extent of this effect is likely to be influenced by the different behaviour and visual abilities of

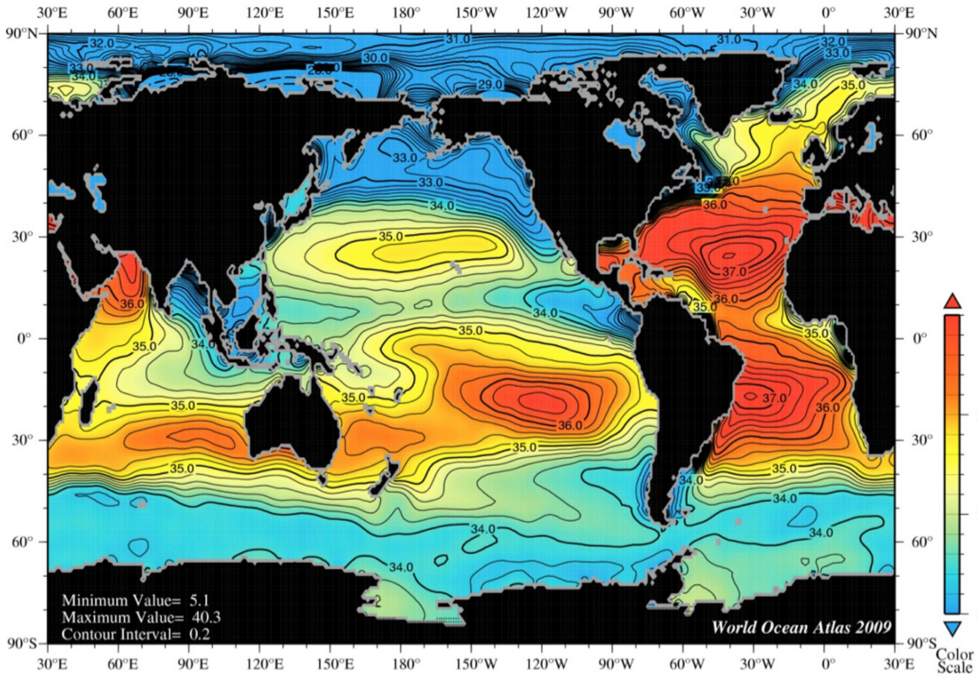
FIGURE 16
Average annual mean wind speed at 10 m elevation for the world's oceans



Source: Huai-Min Zhang, NOAA National Climatic Data Center, www.ncdc.noaa.gov/oa/rsad/seawinds.html

FIGURE 17
Mean annual salinity of surface waters of the world's oceans

Annual salinity (PSS) at the surface



Source: NOAA National Climatic Data Center, www.nodc.noaa.gov

different fish species (Ang and Petrell, 1998). High water transparency can also create husbandry issues for fish species that avoid high light situations (Fernöa *et al*., 1995). Indeed, light that is too intense may be stressful or even lethal for some fish species (Boeuf and Le Bail, 1999). Also, ultraviolet wavelengths from sunlight can penetrate high clarity seawater for a few centimetres especially when the sun's radiation is perpendicular to the Earth's surface, such as in the tropical zone (Beveridge, 2004). This situation creates a risk of ultraviolet burning of the skin of fish species that swim at the surface, a behaviour that sometimes is the result of low oxygen availability in the water (Halver, 1987).

Coastal mariculture in tropical zones in some locations has encountered problems with large fish predators, such as salt water crocodiles and sharks (Murray-Jones, 2004). Moving farms further offshore may reduce interference from large carnivorous reptiles which generally do not venture long distances from the coastline (Elsey, 2005). However, sharks do appear to be attracted to fish farming operations even where they are located some distance offshore (Godvin, 2005; Murray-Jones, 2004). Seabirds can also be a nuisance in preying upon fishes in sea cages and are found in coastal and offshore waters, especially in areas of high natural productivity (Beveridge, 2004).

The mariculture of organisms in open waters may avoid some problems with diseases and parasites. This is likely to be the case in offshore locations that are not frequented by wild populations of the cultured species that could act as a vector for the introduction or transfer of disease and parasites (Buck *et al.*, 2005; Hampson *et al.*, 1999; Naylor and Burke, 2005; Pennell and Barton, 1996). This situation is likely to apply equally to tropical and temperate ocean zones.

Marine mammals, sea turtles and whale sharks have been known to become entangled in mariculture infrastructure (Du Fresne, 2008; Lloyd, 2003; Paul, 2000). Members of these animal groups migrate widely in the oceans, and are frequently found in offshore waters, and some members tend only to be found in offshore waters, e.g. whale sharks and leatherback turtles. Both whale sharks and sea turtles are more commonly found in oceans of the tropical zone (Chen and Phipps, 2002; Spotila, 2004). However, species of marine mammals, both cetaceans and seals, are distributed throughout the world's oceans with some species migrating between temperate and tropical zones. There have been efforts to design remote warning and security systems for aquaculture sites to deal with both nuisance marine mammal predators and for early response for cetacean entanglement (Jackman and Ace-Hopkins, 1993; Paul, 2000).

Conflict of mariculture with other water users tends to decrease with distance from the coast, as does wilful interference, such as theft of aquaculture stock, due to the increased difficulty of access (McCarthy, 2002). In open waters the major users that mariculture comes into conflict with are shipping, naval activities, fishing and offshore petroleum activities.

SUITABLE SPECIES FOR OFF-THE-COAST AND OFFSHORE MARICULTURE

A very wide range of aquaculture species are used throughout the tropical zone, largely because of artisanal mariculture making wide use of local species, often by gathering wild juveniles for on-growing. A smaller number of species or clones of species have been distributed more widely for mariculture in the tropical zone, such as some seaweed species, e.g. *Eucheuma* spp. and *Kappaphycus* spp. (Luxton, 1999). With the profit margins involved in cultivating the currently available commercial seaweeds in the tropical zone it is unlikely that they would able to be commercialized in an off-the-coast or offshore situation. This negative outlook is regardless of the biological feasibility of culturing these species in open waters because of nutrient limitation (Firdausy and Tisdell, 1991; 1993).

Many species of filter feeding shellfish are cultured in the tropical zone, including species of oysters, mussels, clams and scallops. The production of many of these species in nutrient rich coastal waters has been increasing in many parts of the world, such as scallop production in China. Opportunities for production in off-the-coast or in offshore situations are likely to be limited in the tropical zone to areas with naturally high phytoplankton production due to localized nutrient rich current upwelling. Aquaculture in such a situation would require some significant market or production advantages, such as being certified free of pollutants, in order to offset the increased production costs over and above the same species being produced in more accessible coastal waters using existing technology.

The same situation would apply to the range of herbivorous molluscs (e.g. abalones, conch and sea snails, such as top shells), detrital feeding marine organisms (e.g. sea cucumbers, polychaete and sipunculid worms) and carnivorous invertebrates (e.g. whelks, crabs, lobsters and shrimp) that are cultured in the marine waters of the tropical zone mostly on a relatively small scale. For many of these species, the techniques for mariculture in marine sea cages is still in the development stage and are unlikely to be progressed to open water mariculture systems, until more fundamental husbandry and production issues have been resolved.

Finfish have been the major focus of most commercial interest in the development of open water mariculture technology in the tropical zone probably because the cage culture technology is already most advanced for finfish and they are capable of being farmed at high biomass on a large-scale, making the economics potentially more attractive. A number of species have been examined for their suitability for mariculture in offshore systems in tropical waters, and all of them are relatively new aquaculture species and are all fast growing carnivorous species. A wide range of characters make a good finfish sea cage aquaculture species, including fast growth, gregariousness and placid nature, disease and parasite resistance, high meat yield, high food conversion, easy larval production and good market characteristics of the finished product (i.e. high price, large and stable end market) (Engelsen *et al.*, 2004).

Cobia (*Rachycentron canadum*) is a species that is now attracting a great deal of commercial and research attention, especially for offshore mariculture application. The species exhibits extraordinary growth (4–6 kg in a year), with relatively high food conversion (FCR = 1.8) with likely future improvement, and few apparent diseases (Benetti, Clark and Feeley, 1999; Liao, 2003; O'Hanlon *et al.,* 2003). The species has been grown in offshore style sea cages with some initial success in Puerto Rico and in Taiwan Province of China (De Silva and Phillips, 2007). The species is found throughout much of the tropical zone of the world and has potential for development in open water mariculture in many parts of the world.

The mutton snapper (*Lutjanus analis*) was selected as one species that could be suitable for offshore style sea cages, including for pilot commercial scale operations in Puerto Rico, Bahamas and for the Gulf of Mexico (Benetti *et al.*, 2006; Benetti, Clark and Feeley, 1999; Benetti *et al.*, 2002; O'Hanlon *et al.,* 2003; Rotman *et al.*, 2003). This species tends to have slower growth than some other species, such as cobia.

A number of other finfish species indigenous to the Gulf of Mexico have also been identified as candidate species for open water mariculture which are characterized by good grow-out and market potential characteristics, including red drum (*Sciaenops ocellatus*) and red snapper (*Lutjanus campechanus*) (Bridger, 2004; Bridger *et al.*, 2003).

Amberjack species (*Seriola* spp.) are fast growing pelagic fish that are often identified as species with strong potential for open water mariculture. The greater amberjack (*Seriola dumerili*) has been identified as a candidate species for the Gulf of Mexico, and a Hawaiian amberjack species (*Seriola rivoliana*) is produced in offshore sea cage technology in Hawaiian waters (Benetti, Clark and Feeley, 1999; Corbin, 2006; Rotman *et al.*, 2003).

Another species with potential in Hawaii is known locally as "moi" or Pacific threadfin (*Polydactylus sexfilis*) and has been produced in a commercial-sized submersible sea cage in open coastal waters 1.6 km from shore (Brown *et al.*, 2002; Corbin, 2006).

There has been increasing production of a wide range of grouper species in Asia in recent years largely driven by their excellent eating qualities and good market prices, especially in live seafood markets in parts of Asia (De Silva and Phillips, 2007). Most production is currently in small family operated sea cages in shallow coastal waters and estuarine areas, although some of these species have excellent potential for large-scale commercial sea cage production.

Asian seabass or barramundi (*Lates calcarifer*) is another species for which production has been increasing in Asia over the past ten years and is becoming the focus of commercial scale sea cage farming in parts of Asia (De Silva and Phillips, 2007). The species also appears to have good prospects for sea cage mariculture in open waters.

FUTURE DEVELOPMENT OF OFF-THE-COAST AND OFFSHORE MARICULTURE

Technology for off-the-coast mariculture is well developed and is established in production systems in many parts of the developed world, especially for finfish production and less so for filter feeding shellfish production. In most instances, the development and application of this technology is the result of extending existing coastal mariculture activities further from the coast due to constraints on mariculture space in nearshore coastal waters. However, off-the-coast technology and capabilities do not appear to be present at any significant level in developing nations. This may be because many of these nations have not encountered or placed effective constraints on coastal space for mariculture. It may also be because a great deal of aquaculture in developing nations is extensive, low technology and run by small enterprises (usually families), rather than larger and more intensive corporate enterprises using more advanced technologies.

This situation appears to be changing, with increasing involvement of foreign-owned aquaculture corporate entities that are involved in establishing new operations in developing nations, and in so doing, delivering capital, technology and expertize, especially for finfish production. The motivation for investment by these companies is low labour costs and access to coastal growing waters, both of which are typically much less available in the developed countries in which these companies are usually based. Many of these developing countries, particularly in Asia, have previously demonstrated remarkable abilities to rapidly absorb, adopt and replicate new seafood technologies (e.g. development of shrimp aquaculture and seafood processing). Further rapid expansion of mariculture production in coastal waters in developing countries is likely to lead to pressures to move mariculture further from the coast to avoid competing coastal uses, especially coastal pollution which is an increasingly common feature of many developing countries in the tropical zone. These pressures will undoubtedly lead to the importation and local development of off-the-coast mariculture production, by building off the confidence of a well-established inshore mariculture industry.

Technology for offshore mariculture is not as well developed for commercial application as off-the-coast mariculture technology because it involves more than adaptation of existing aquaculture infrastructure. Offshore mariculture technology is mostly being driven by research and commercial interests in developed countries, but with many of them operating in the tropical zone, such as Hawaii (USA), Bahamas, Gulf of Mexico and Puerto Rico. Consequently, it is likely that future development and commercialization of this offshore technology will be in the tropical zone, but driven by commercial and research interests from developed nations, and within developing countries. However, this commercial development may take some time given that there is significant capacity for development of coastal mariculture in many developing nations in the tropical zone. Therefore, it is likely to be less costly to use existing and well-proven production technology closer to the coast, than utilize more costly offshore mariculture technology. In time this situation will change as increasing pressures on coastal resources encourage the use of waters further from the coast for mariculture expansion.

Recent interest in the development of energy production from the ocean (wind, wave and currents) may create synergistic opportunities for open water mariculture by establishing mooring and servicing infrastructure for energy production. However, similar opportunities for synergies with mariculture have previously been expressed in relation to offshore oil and gas infrastructure, but have not eventuated on any scale.

There are likely to be regional differences in the development of off-the-coast and offshore mariculture, with Asia continuing its rapid expansion of mariculture activities whilst other regions, such as Africa and Latin America and the Caribbean may move at a slower pace despite dramatic increases in seafood demand expected in parts of these regions (Brugère and Ridler, 2004; Jamu and Ayinla, 2003).

A large number of studies and projects have investigated and responded to the needs of developing countries for advancing mariculture, often providing substantial direct assistance with finances and capability. This sector is also well served by agencies such as WorldFish Center (WFC), Network of Aquaculture Centres in Asia-Pacific (NACA), Southeast Asian Fisheries Development Center (SEAFDEC), Sarnissa, the World Bank, Asian Development Bank, the Food and Agriculture Organization of the United Nations, in addition to the foreign assistance agencies operated by many developed countries. It is widely accepted that aquaculture development has the potential to provide a wide range of social and economic benefits to developing countries including, domestic food security, vital micronutrients (omega-3 oil) to domestic populations, foreign currency, relieving pressure on wild fisheries, as well as providing employment and economic development in rural communities.

There are a wide range of areas that have been identified as having the potential to provide improved aquaculture, especially in developing nations in the tropical zone.

Technical assistance is commonly identified as an important priority for assisting developing nations (Ackefors, Huner and Konikoff, 1994; Corbin and Young, 1997; Hanson, 1974a; 1974b; Lovatelli *et al*., 2008; Nash and Fairgrieve, 2007; The World Bank, 1991a; 1991b; 1991c; 1991d). Typically, this includes providing technical assistance in almost every area of aquaculture activity including, research, aquaculture technology in all production areas, training and experience for personnel, market knowledge, value adding, as well as the development of regional and international technical networks.

Improving the governance of aquaculture is also an area that is commonly identified as a priority for international assistance for developing nations including, better knowledge and systems for the management of aquaculture environmental impacts and diseases, aquaculture licencing, policy and implementation, as well as national and regional planning and promotion of aquaculture (Ahmed, Dey and Garcia, 2007; Lovatelli *et al.*, 2008; Nash, 1995; Nash and Fairgrieve, 2007; OECD, 2010). For example, the development and implementation of national aquaculture plans has recently been recommended as a priority for mariculture producing countries (OECD, 2010).

Among these previously identified priorities, assistance with the development of offshore mariculture is rarely, if ever, mentioned. This is probably because these nations are dealing with pressing issues associated with promoting and managing the development of existing inshore mariculture activities, so that open water mariculture is not seen as an immediate priority.

The growth and the orderly management of nearshore mariculture activities will ultimately lead to off-the-coast and offshore mariculture development as it has in developed nations. There are also some indications that off-the-coast mariculture developments may arrive sooner in some developing countries via foreign aquaculture companies attracted by substantial areas of new farming space and low labour costs, but wanting to avoid the growing inshore pollution and poor mariculture management regimes (e.g. disease control) which is commonplace in many developing nations in the tropical zone (Alongi *et al.*, 2003; Beveridge, 2004; Stickney, 1997). However, one of the main constraints for attracting domestic and foreign sources of capital investment and capability in aquaculture development continues to be the policy environment and political stability in developing countries in the tropical zone (Brugère and Ridler, 2004). Creating conditions that are conducive to investment by commercial aquaculture interests is thought to be a vital precursor for successful growth in aquaculture sectors in developing countries (Hishamunda, 2007; Jamu and Ayinla, 2003).

In contrast to developing countries, offshore mariculture is more prominent among the priority areas often identified for aquaculture development in developed countries. For example, in the United States of America the advancement of offshore mariculture technology through the improved automation and monitoring of offshore farming, an ability to supply and transport large batches of fish fingerlings to stock offshore farms have been identified as research priorities by aquaculture industry leaders (Browdy and Hargreaves, 2009). Similar sets of priorities that indicate the greater focus on advancing offshore mariculture are commonplace among other developed nations (Ágústsson, 2004; James and Slaski, 2006; NAC, 2007; Ryan, 2004; Ryan, Jackson and Maguire, 2007).

There are also international initiatives to promote open ocean mariculture including international conferences every two years, with the next planned for Izmir, Turkey, in October 2012 (www.offshoremariculture.com). The International Council for Offshore Aquaculture Development (ICOAD) was formed out of a similar conference "Farming the Deep Blue Conference" held in Ireland in 2004. The ICOAD has the aim of proposing "suitable technologies and methodologies for successful aquaculture operations in the offshore zone." The ICOAD was subsequently associated with a European Union-funded project to advance offshore mariculture technology which included some co-ordination work among European groups interested in advancing offshore mariculture (Ryan, 2004; Ryan, Jackson and Maguire, 2007). Encouraging more international collaboration and international sharing of technological developments is likely to assist in progressing open ocean mariculture, including for developing countries.

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Sustainable development of marine aquaculture off-the-coast and offshore – a review of environmental and ecosystem issues and future needs in temperate zones

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ABSTRACT

Aquaculture is predicted to move offshore in the near future and this review addresses the interactions between aquaculture and the environment under offshore conditions. Most environmental impacts are predicted to decline, as the dispersion of waste products is increased under offshore conditions due to larger water depths and stronger currents and winds. The benthic communities may, however, be more sensitive to organic loading, as deep sea fauna is adapted to low organic matter inputs. The attraction of wild fish and interactions with fisheries may be the same as at near shore farms, whereas the carbon footprint increases due to higher energy use for transportation and the risk of escapees increases in the larger farms placed under rough weather conditions. Some major gaps of knowledge in predicting environmental impacts under offshore conditions are the lack of knowledge on the deep sea communities and in particular on habitats sensitive to organic matter inputs. Experimental evidence of organic matter enrichment is needed to understand the assimilative capacity of deep sea sediments, as well as the response of the infauna to organic loading. Also knowledge on cultured and wild fish with respect to genetic, disease and parasitic interactions need further examination before farming offshore can be recommended.

CHARACTERISTICS OF OFF-THE-COAST AND OFFSHORE AQUACULTURE IN TEMPERATE ZONES

Introduction

Based on the high expectations for development of aquaculture, offshore mariculture has received considerable attention over the last decade. While present marine aquaculture production mainly takes place in nearshore farms there is a successive move towards offshore sites. Pushed by the overall highly competitive use of coastal seas, the scarcity for available space has increased. In addition, the existence of good water qualities in the open ocean such as oxygen conditions, less pollution, less eutrophication, has acted as "pull" factor for offshore developments. The motivations for movement include environmental aspects of intensive cultivation of particular fish in cages, and compared to coastal farming, offshore locations are more exposed increasing the dispersal of both dissolved and particulate waste products. The development within offshore production during the last decade has, however, focused on finding technology solutions and suitable sites, whereas less focus has been on the environmental issues of offshore production. The technological development seems now to be in such an advanced stage, that offshore production is going to take place. There are regular reports in the media on expansion of offshore production, even in these years despite major constrains, such as the financial crisis and the major losses encountered for salmon production in Chile and cod production in Norway, due to disease and declining prices, respectively. As an example, Marine Harvest just announced plans for investing £40 million in four farms in Scotland, which all together will produce 20 000 tonnes of salmon. GreatBay Aquaculture in the United States of America is planning a farm consisting of single cages hosting up to 25 000 whitefish located 3–20 miles offshore, and New Zealand is planning a 2 695 hectare of mussel farms, which will generate 200 jobs. The prospects for offshore development are thus quite optimistic.

Scientific publications on environmental issues at offshore farms, as defined in this review (Table 1), are not available. The few published studies are from test sites with low fish production or report ideas on possible environmental constrains. Much more peer-reviewed information is available for "off-the-coast" farming, although it can be difficult to find this information, as only few publications distinguish between coastal and off-the-coast farming. At present up to half of salmon production in Norway can be characterized as "off-the-coast", but the Norwegians consistently refer to coastal aquaculture production. Documented evidence of environmental effects are thus limited for offshore farming (<10 farms in temperate waters) and from off-the-coast farms difficult to find, and this review will therefore use both results available from existing farms, and include more theoretical considerations of possible environmental effects of aquaculture in particular for offshore farms. The review is further constrained by the significant gaps in scientific knowledge from particularly deep sea habitats. For instance, little is known about the dispersal of many deep-sea organisms, which may have clear consequences for the impacts on sediments and for prediction of the success of fallowing practices. Mapping coverage of sensitive habitats in the deep sea is also low, with the majority of effort targeted towards areas containing clearly identifiable habitats such as cold-water coral reefs (e.g. Roberts and Hirshfield, 2004). Current distribution data of mobile species such as deep-sea fish are poor, with many migration routes and aggregation areas currently unknown (Haedrich, Merrett and O'Dea, 2001). Without sound scientific knowledge, detailed species distributional and abundance data and physical habitat mapping, it is difficult to predict impacts of aquaculture activities in offshore zones. Such research gaps will be addressed in the dedicated section in the end of this review.

Definition of off-the-coast and offshore

According to the definitions given for off-the-coast and offshore production by FAO (Table 1), off-the-coast production differs from coastal aquaculture primarily by the distance to the coast and the degree of exposure (Table 1). Off-the-coast takes place in a zone from 500 m and up to 3 km from shore in water depths between 10 and 50 m. The sites can be protected, but currents are stronger, and wind and wave effects more severe compared to fish production closer to shore. Offshore production is located 2 km or

TABLE 1
Definitions for coastal, off-the-coast and offshore aquaculture based on some environment and hydrographic characteristics. Present study will not involve directly "coastal aquaculture"

	Coastal	Off-the-coast	Offshore
Location/ hydrography	< than 500 m from the coast $\leq$10 m depth at low tide; within sight usually sheltered	500 m–3 km, 10 m < depth at low tide $\leq$50 m; 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 $\leq$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, etc.	Some automated operations, e.g. feeding, monitoring	Remote operations, automated feeding, distance monitoring, system function

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

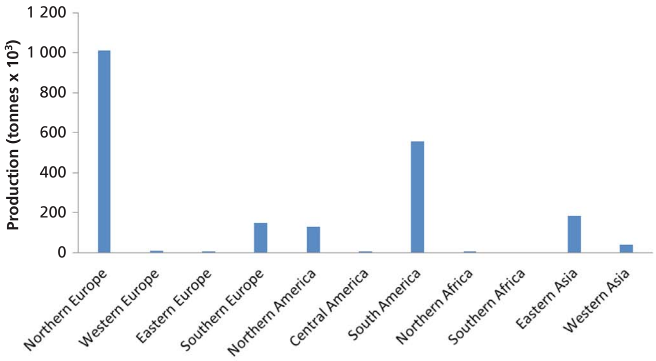
more from the shore in water depths >50 m with influence of ocean swells, strong winds and ocean currents. Annual fish production in the off-the-coast and offshore cage cultures is expected to be >1 000 tonnes, and perhaps up to 10 000 tonnes of fish. The production principles are, however, the same as for coastal production, i.e. fish will by cultured in net cages, dry feed pellets will be the main food source and the fish species already being cultivated will also be the main cultivated species in off-the-coast and offshore, but with use of more sophisticated and remote controlled feeding and monitoring systems. Also shellfish and algae cultivation has been proposed for off-the-coast and offshore production with principles similar to coastal aquaculture.

Current off-the-coast and offshore activities in the temperate zone

Due to the high cost and high technical skills required for offshore production, it can be expected that major aquaculture producing countries are the first to expand to offshore sites, in particular because the move is stimulated by the existing pressures on coastal zones, which is largest in countries with a high production. Most of the current temperate fish production in marine aquaculture is located in Northern Europe (40 percent), followed by South America (27 percent) with two dominating countries (Norway and Chile), whereas the production is rather equally distributed between a range of countries in other temperate zones (Figure 1, Table 2). Salmon is the dominant fish in aquaculture, with Norway as the largest producer followed by Chile until 2007, although this scenario will be likely different in 2008–2009 due to disease and collapse of the Atlantic salmon industry in Chile (see Alvial this volume). Production of salmon is around 10 times higher than seabream/seabass, which are the second largest fish species in aquaculture. China has the highest production of seabream/bass, followed by the Mediterranean Sea, with Greece as the largest producer. For shellfish, the Republic of Korea and Japan have very high production, while Spain also has a high output, approximately twice as high as the following countries: France, Chile and the United States of America. It is mainly these three groups of organisms (salmon, seabream/seabass and shellfish), which are projected for offshore production, but also other species such as cod, tuna, white fish and seaweeds are considered for offshore production (Buck and Buchholz, 2005; Troell *et al.*, 2009). All species are grown already under off-the-coast conditions.

Norway does not define their aquaculture production as off-the-coast or offshore, but use the term "coastal production". The trend over the past ten years has nonetheless been moving the farms to still greater water depth and still farther out into the outer parts of fjords and out from the coasts. It is estimated that about 50 percent of production

FIGURE 1
Temperate production of salmon, seabream/seabass by regions in 2007



Sources: Global dataset of aquaculture production (quantity and value) 1950-2008. Released in March 2010, by the Fisheries and Aquaculture Statistics and Information Service, FAO.

can be defined as off-the-coast (for all parameters) and some of these even offshore (in terms of depth, but not by environment and access according to Table 1). In Spain, some of the fish farms are defined as off-the-coast/offshore. These are typically located several kilometers from shore in water depths <50 m with a wave intensity Hs <3–4 m, and are thus contained in the off-the-coast category. It is likely that some fish farms in the Mediterranean Sea are located at similar off-the-coast locations as in Spain, and tuna are typically farmed on off-the-coast locations. Also in the Faroe Islands, Chile and Canada, salmon are farmed in deep waters, but farms are often protected by their extensive archipelago and fjord systems. In a New Hampshire (USA) test site, experiments have been going on for several years using offshore technologies although at relatively low fish production. These studies include environmental monitoring of water quality, sediment and benthic fauna. Fish farming occurs at several off coast locations in the tropics (e.g. Caribbean), and since there is limited data available, only few of these cases will be included in this review. The areas considered suitable for offshore farming by depth ranges within EEZ's are shown in Figure 2.

TABLE 2
Top 10 countries in the production of salmon, seabream/seabass and shellfish in 2007

Salmon and rainbow trout (mt)		Seabream/seabass (mt)		Shellfish (mt)	
Norway	813 746	China	100 574	Republic of Korea	536 863
Chile	553 956	Greece	84 423	Japan	451 700
Canada	117 306	Japan	67 000	Spain	214 701
United Kingdom	132 457	Turkey	33 500	France	180 070
Faroe Islands	29 954	Spain	25 828	Chile	171 317
Australia[1]	20 000	Italy	14 351	United States of America	159 225
United States of America	11 001	Korea	12 415	New Zealand	102 508
Ireland	10 430	France	4 840	Netherlands	101 556
Denmark	6 882	Croatia	3 950	Ireland	45 866
France	1 168	Portugal	3 321	Canada	38 864
Total	**1 696 900**		**350 202**		**2 002 670**

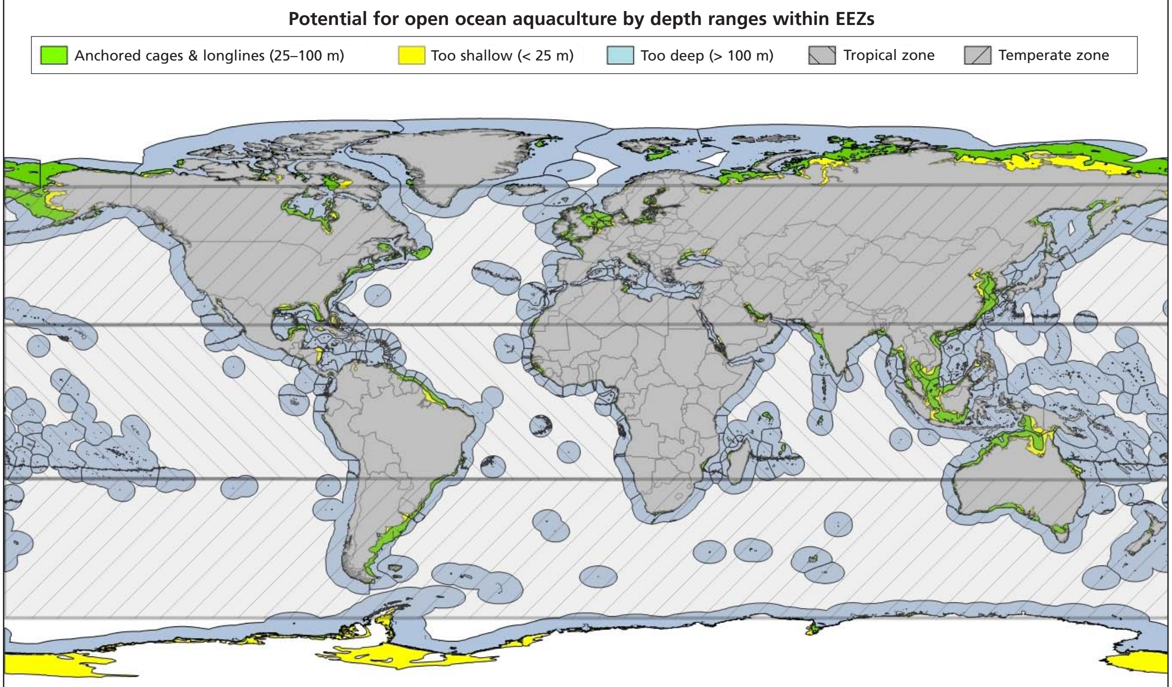
[1] Estimated – data not available in FAO FishStat

Source: Global dataset of aquaculture production (quantity and value) 1950–2008. Released in March 2010, by the Fisheries and Aquaculture Statistics and Information Service, FAO.

ENVIRONMENTAL INTERACTIONS OF OFF-THE-COAST AND OFFSHORE PRODUCTION

Off-the-coast and offshore sites are characterized by greater depth and greater exposure compared with coastal sites. This means that the dispersion of waste products as the starting point is higher, partly due to stronger currents and wind effects and partly due to the greater water depth. It is, however, important to stress that hydrodynamics and bottom configuration can play an important role also in more exposed areas. In addition, the water column may be stratified due to temperature or salinity, affecting the sedimentation regime of waste products. Local variations in currents due to bottom topography (sills, basins) may also affect the dispersal of waste products. At present available data on offshore currents and hydrodynamics are limited, in particular at local scales, beyond ocean models. This is further constrained by the difficulty to obtain

FIGURE 2
Potential locations for offshore farming under temperate and tropical conditions



Source: Kapetsky, Aguilar-Manjarrez and Jenness, 2013.

information due to high costs of ship operation and expensive equipment, and hamper the planning and siting of aquaculture activities in off-the-coast and offshore locations. Furthermore, it is important to consider the predicted size of the farms, which is often larger with typically 1–2 times higher annual productions (2–3 000 tonnes) compared to coastal production, increasing the discharge of waste products from each farm substantially.

Water quality at offshore and off-the-coast locations is possibly different from the coastal zones, displaying lower concentrations of nutrients and lower biological productivity. However, some off-the-coast and offshore locations are potentially very productive such as the North Sea and limited by seasonal variation in light rather than nutrients. This could play a role for the fate of dissolved nutrients from farms. Other water quality parameters, such as concentrations of toxins, chemicals and pollutants in general are expected to be lower at off-the-coast and offshore locations and thus beneficial for farm production, whereas the release of such compounds from farms may have greater impact due to higher sensitivity of these pristine environments.

The sedimentation of waste products from off-the-coast and offshore aquaculture production, and thus the input to the benthic compartment, will depend on a range of different factors, including source of sedimentation (feed pellets, composition of feed pellets, faeces, fish species, etc.), means of transport and rate of supply. The sediment conditions in deep locations could be coarser-grained and more advective sediments compared to coastal sites, propagated by the flow regimes in exposed areas. The sediments at advective sites would consist of shell sands or coarse grained carbonate sediments. Most deep sea sediments are, however, fine grained as a consequence of (low) sedimentation of fine particles and deposition of coarser material near the coast. One important aspect of the deeper sites is permanent low water temperatures and less light, which reduces the overall biological activity. Deep sediments can, to some extent, be considered less productive and carbon-starved with a lower fauna biomass and diversity compared to coastal zones, although there are areas of high productivity such as in vent areas and upwelling zones. Potential off-the-coast and offshore sites may also host a variety of sensitive habitats, such as cold-water corals and sponges.

Two of the most important factors distinguishing deep from shallow areas are lack of light penetration to the seafloor and the limited distribution of hard substrate with its associated flora and fauna. Presence of light controlled sensitive habitats such as seagrass meadows, algae on reefs, and other benthic vegetation is less in deep locations, and as these are particularly sensitive to fish farm waste products, movement to deeper locations is an environmental benefit (Holmer, Perez and Duarte, 2003). Light may, however, still play important roles in off-the-coast locations, in particular in the Mediterranean Sea with deep light penetration. Hard substrates are associated with the coast and thus most abundant closer to shores, but are also present in areas with strong bottom currents. In the last case, rapid dispersal probably limits the sedimentation of waste products.

Finally, impacts related to disease and escapees have similarities to coastal production, but also differences due to the location farther from shore, and will be addressed below.

Water quality

Due to a rapid dilution of nutrients from marine aquaculture, it is difficult to detect elevated nutrient concentrations around fish farms by direct measures, but use of bio-assays have shown increased nutrient availability for several hundred meters away from coastal cages (Dalsgaard and Krause-Jensen, 2006). Also by the use of a modified bio-assay approach, it was found that under oligotrophic conditions nutrients are transferred rapidly up the food chain, where they are available as food for higher organisms (Pitta *et al.*, 2009). Due to even higher dispersion at off-the-coast and offshore farms compared to coastal aquaculture, the use of bio-assays will be useful to measure the nutrient release at these locations.

Depending on location, pelagic primary production in off-the-coast and offshore waterbodies can be limited by nitrogen (often the case in the Atlantic) or by phosphate (in the Mediterranean) or light (in high latitudes). A combination of all three factors may also be the case, e.g. over a seasonal cycle. Coastal areas are generally limited by phosphate due to high nitrogen load from watersheds, but often with seasonal variations in nutrient limitation, and both nutrients may be limiting in the summer period (Conley *et al.*, 2009). Phosphate limitation is shifted to nitrogen limitation in open waters, and by placing fish farms at off-the-coast or offshore locations, nutrient release may have quite different impacts compared to coastal conditions. As there is a high release of nitrogen from fish farms in the form of ammonium, this may enhance the primary production in farm vicinities in open waters, although in the Mediterranean Sea nitrogen stimulation would depend on the availability of phosphate. Phosphate is, however, also an important waste product from fish farms, mostly in particulate form, and enhanced mineralization in the deeper water columns could regenerate phosphate for uptake by phytoplankton.

Impacts of nutrient enrichment on pelagic primary production in open waters have to some extent been studied experimentally, and some of the results are of interest for fish farming in off-the-coast and offshore locations. Probably the most widely known experiments are those in Antarctic, where fertilization of the water column with iron has been done, as iron is considered the limiting nutrient in these relatively nutrient (N, P) rich locations. A general observation from nutrient addition (N, P and Si) studies in temperate waters is a response of the lower trophic levels with increase in primary production (McAndrew *et al.*, 2007). The composition of the phytoplankton community change from small (<2 μm) to large species (>10 μm), and is often dominated by diatoms (McAndrew *et al.*, 2007). When dissolved organic matter is added experimentally to the water column as well, the microbial food web is also stimulated, in particular, if nutrients are added at the same time (Havskum *et al.*, 2003). Such a scenario is likely for fish farms, as dissolved organic matter leaks from wasted feed pellets and faeces along with the dissolved inorganic nutrients released directly from the fish or faeces, and are consistent with findings by Navarro, Leakey and Black (2008). They measured enhanced bacterial activity in the vicinity of a fish farm in a Scottish Loch with somewhat restricted water flow. Higher dispersion at off-the-coast and offshore locations may limit the activity, but it is possible that fish farming in off-the-coast and offshore locations will stimulate both bacterial activity and phytoplankton growth, with potential transfer to higher trophic levels through an efficient grazer food web (Pitta *et al.*, 2009). The pelagic productivity at higher latitudes will most likely show large seasonal variation, controlled by light and nutrient availability (Dandonneau *et al.*, 2004), and linked to farm production through nutrient release, as well as seasonal variation in grazing intensity. In the Mediterranean the seasonality may be less, as the productivity to a larger extent is controlled by nutrient availability, but light conditions, seasonal variation in temperature and farm production has to be considered as well (Psarra, Tselepides and Ignatiades, 2000).

Observed impacts on water quality

The few studies examining water quality and primary productivity near off-the-coast and offshore farms show no measurable change in nutrient concentrations (Table 3), but techniques like bio-assays, which are able to capture nutrients released from the farms into biomass growth, have not been applied yet. Using bio-assays at off-the-coast locations in the Mediterranean showed enhanced nutrient availability up to 150 m

TABLE 3
Overview of documented environmental impacts of temperate off-the-coast (OFC) and offshore (OFS) finfish and shellfish cultures divided into water quality, impacts on sediments and on the benthic fauna

Study	Type	Location	Water quality	Sediment	Fauna	Comment	Reference
Seabream/ seabass	OFS	East Mediterranean	No impact	No data	No data	–	(Basaran, Aksu and Egemen, 2007)
Seabream	OFS	Canaries	No data	Enhanced ON pools under cages	–	Low production	(Dominguez *et al.*, 2001)
Shellfish/ flounder	OFS	USA	No impact	No impact	No impact	Low production	(Grizzle *et al.*, 2003)
Atlantic tuna	OFC	West Mediterranean	No data	Enhanced OM pools and bacterial activity, reduced sediments	Disturbed community	–	(Vezzulli *et al.*, 2008)
Atlantic tuna	OFC	Adriatic	No impact	Enhanced P pools	No data	–	(Matijevic, Kuspilic and Baric, 2006)
Cobia	OFC	Puerto Rico	No data	Enhanced ON pools under cages	No data	–	(Rapp *et al.*, 2007)
Salmon	OFC	Norway	No data	Increased sedimentation, increased P content	See below	230 m water depth. Waste signals in bottom traps up to 900 m away	(Kutti, Ervik and Hasen, 2007)
Salmon	OFC	Norway	No data	Reduced sediments <250 m, no change in OM pools except P	Increased production, abundance, biomass, reduction in diversity	230 m water depth	(Kutti, Ervik and Hoisaeter, 2008; Kutti *et al.*, 2007)
Salmon	OFC	Chile	No impact	Enhanced OM pools	Decreased species richness	15–94 m water depth	(Soto and Norambuena, 2004)
Seabream/ seabass	OFC	West Mediterranean	No impact	Enhanced OM pools under cages	Reduced species richness and abundance	Impact at 2 out of 5 farms	(Maldonado *et al.*, 2005)
Seabream/ meagre	OFC	West Mediterranean	No data	Enhanced OM pools under cages	Disturbed community		Tomasetti *et al.*, 2009

TABLE 3 (CONTINUED)

Study	Type	Location	Water quality	Sediment	Fauna	Comment	Reference
Seabream/ meagre	OFC	West Mediterranean	No data	Enhanced OM pools under cages and downstream	Reduced species richness and abundance	–	(Aguado-Gimenez *et al.*, 2007)
Seabream/ seabass	OFC	Mediterranean	No data	Enhanced P pools	Abundance shifts	Seagrass impacted	(Apostolaki *et al.*, 2007)
Seabream/ seabass	OFC	Mediterranean	Nutrient availability enhanced up to 150 m	–	–	MedVeg project	(Dalsgaard and Krause-Jensen, 2006)
Seabream/ seabass	OFC	East Mediterranean	Transfer to higher trophic levels	No data	No data	–	(Pitta *et al.*, 2009)
Seabream/ seabass	OFC	Mediterranean	–	–	Enhanced seagrass mortality	MedVeg project	(Diaz-Almela *et al.*, 2008)
Seabream/ seabass	OFC	Mediterranean	–	Enhanced OM pools and bacterial activity, reduced sediments	–	MedVeg project	(Holmer and Frederiksen 2007; Holmer *et al.*, 2007)
Tuna	OFC	Spain	No data	No change in OM pools	Disturbed community up to 220 m away	–	(Vita *et al.*, 2004a)
Blue mussels	Coastal	Canada	No data	Enhanced OM pools and reduced sediments	–	–	(Cranford, Hargrave and Doucette, 2009)

ON: organic nitrogen; OM: organic matter; P: phosphorus.

(Dalsgaard and Krause-Jensen, 2006). A study in oligotrophic eastern Mediterranean at a off-the-coast site showed rapid transfer of nutrients to higher tropic levels (Pitta *et al.*, 2009), and a study of fisheries in the same area showed positive correlation between aquaculture production and landings, suggesting a transfer of wasted nutrients to higher trophic levels (Machias *et al.*, 2005). At the New Hampshire test site various water quality parameters have been measured over time, such as total suspended matter in the water column and dissolved oxygen (Ward, 2001). The New Hampshire test site is a research offshore farm financed by the University of New Hampshire, USA. It is located ten km from shore at 55 m of water, and has a varying production of fish (haddock, turbot) in up to four submerged cages. Each cage has a diameter of 25 m with a lower production of fish compared to commercial-scale, but it has not been possible to find production numbers for the different years investigated. Neither the total suspended matter nor chlorophyll-a concentrations showed major variation between farm and upstream and downstream stations. There were seasonal trends in concentrations and organic contents in response to phytoplankton blooms or storm events, but all values observed were within expected ranges for the various depths, seasons and locations on the inner shelf of New Hampshire. Based on these results, no evidence of the aquaculture production affecting these water quality parameters was observed. The dissolved oxygen saturation values were typically 100 percent or greater (saturated or supersaturated) near the surface and then decreased with depth at all stations independent from the location of the farm. The lower percentage saturation near the bottom was attributed to cooling of the water column and the annual variations in dissolved oxygen concentrations that occur in this region of the Gulf of Maine. The study concluded that no changes in the dissolved oxygen concentrations could be attributed to the aquaculture activities.

Bottom habitats

Enrichment of the benthic environments as a result of fast sinking particulate waste products from farms is considered one of the most significant impacts of marine aquaculture (Hargrave, Holmer and Newcombe, 2008). Under offshore and off-the-coast conditions, waste products are believed to be dispersed over larger areas, but due to the fast sinking rates of feed pellets and faeces (Cromey, Nickell, and Black, 2002; Magill, Thetmeyer and Cromey, 2006), sedimentation can be expected in the immediate vicinity of the farms (hundreds of meters). As deep sediments generally are considered carbon limited (Carney, 2005), inputs of waste particles are increasing the supply of a limiting factor in these relatively low organic content environments, and thus, potentially stimulating productivity of benthic fauna in the sediments. Carbon starved benthic fauna typically respond to organic enrichment with increasing total community density and wet weight (biomass) as a result of increased energy flow through the community, whereas the diversity is reduced (Gallucci *et al.*, 2008; Nilsson and Rosenberg, 2003; Pearson and Rosenberg, 1978). Hence, if organic waste deposition from excess feed pellets and faeces are affecting the benthos, a pattern of increased densities and biomass is to be expected in impacted zones. On the other hand, the microbial processes also respond to organic enrichment by enhancing their activity, and thereby increase the risk of hypoxia and reduced conditions in the sediments. Occurrence of hypoxia affects the benthic fauna negatively, but areas where hypoxia occurs are frequently areas that are stagnant or with poor water exchange (Gray, Wu and Or, 2002). Thus, hydrographic factors are key processes determining whether or not hypoxia occurs. Offshore and off-the-coast locations should have less risk of hypoxia, although local hydrographic conditions have to be considered. Furthermore, deep-dwelling benthic fauna, which are expected to be abundant in deep sediments, may suffer from sulfide toxicity at higher oxygen concentrations, due to reduced conditions in the sediments (Hargrave, Holmer and Newcombe, 2008).

A major difference between shallow and deep water is a lower biomass of benthic fauna with lower bioturbation activity in the later (Snelgrove and Smith, 2002). Studies of bioturbation activity in deep sediments are few, possibly constrained by the high costs and difficulties of operation under such conditions (Hughes and Gage, 2004). Importance of bioturbation activity has been studied experimentally in fish farm sediments (Heilskov, Alperin and Holmer, 2006; Heilskov and Holmer, 2003; Valdemarsen, Kristensen and Holmer, 2009). The extent of bioturbation plays a major role in the supplement of electron acceptors to complement the microbial processes (Valdemarsen, Kristensen and Holmer, 2009) and a lower activity may lead to a depletion of e-acceptors and a shift in the bacterial processes from dominance of aerobic respiration to sulfate reduction and possibly methanogenesis, if sulfate is depleted (Holmer and Kristensen, 1994). Enhanced sulfate reduction, and thus sulfide production, may eliminate the benthic fauna as a result of reduced conditions and anoxia (Hargrave, Holmer and Newcombe, 2008). This is particularly a problem in the fine-grained sediments with low advection, and also a potential problem in coarse-grained deep sediments due to low iron pools (Valdemarsen, Kristensen and Holmer, 2009). Heilskov, Alperin and Holmer (2006), however, found limited accumulation of sulfides in coarse-grained carbonate fish farm sediments stimulated by high bioturbation activity, whereas high sulfide concentrations were found in the similar sediments, when no fauna was present (Holmer and Frederiksen, 2007). Unpublished results from Norway show low accumulation of organic matter, if any in coarse-grained sediments, since the organic material is transported away from the farming sites (R. Bannister, personal communication, 2010). Deposition of organic material in shell sand can potentially lead to dramatic effects, since the presence of benthic fauna is likely low in these carbon limited sediments, and microbial degradation will probably be the dominant degradation process for the deposited organic material. Advection of exposed sediments can provide e-acceptors to the bacteria, while a lack of advection may result in a shift towards reduced conditions with high sulfide pools, as shell sands have limited capacity to bind sulfide with iron (Holmer and Frederiksen, 2007). Shell sands contain low levels of iron due to their carbonate nature. Due to the potential large dispersion of waste products from marine aquaculture at exposed locations, it is important to monitor far-field effects in nearby sedimentation basins, which are likely receivers of dispersed organic matter, although the sedimentation is expected to be less than at coastal sites.

Sedimentation of waste products in areas experiencing seasonal or annual oxygen depletion events should clearly be avoided, as organic matter inputs can increase the duration and extent of oxygen depletion, and as the frequency and distribution of these zones are increasing rapidly in coastal zones of industrialized countries (Diaz and Rosenberg, 2008), this is important to consider when planning aquaculture expansion. In contrast to deep sediments, there are more experimental enrichment studies of shallow sediments, and some of them have focused on the fate of fish farm waste products (see above). Generally these studies show extreme high rates of bacterial decomposition, stimulated by the high nutrient contents of the waste products. The nutrient contents and bacterial lability of the organic matter in feed pellets and faeces are much higher compared to phytoplanktonic detritus, concentrating the supply of organic matter to the sediments even at relatively low rates of sedimentation and enhancing microbial degradation much more that marine derived organic matter (Valdemarsen, Kristensen and Holmer, 2009). Most studies have been undertaken either in defaunated sediments or in sediments with relatively tolerant benthic fauna, such as polychaetes of varying size. These studies show a certain capacity for decomposition of organic waste products, but the capacity is very limited in defaunated sediments leading to accumulation of organic matter. With fauna present the capacities vary with sedimentation regime and abundance, biomass, bioturbation mode and diversity, and a range of threshold values for maintaining the benthic communities in enriched sediments have been determined (Findlay and Watling, 1997; Kutti, Ervik and Hoisaeter, 2008; Valdemarsen, Kristensen and Holmer, 2009). Similar experiments will be useful for the deep sea sediments, and one of the first issues to include, is the fact that both benthic fauna activity as well as microbial activity can be up to several orders of magnitude lower than found in coastal sediments. This may affect the threshold values for organic matter decomposition significantly towards lower enrichment tolerance.

Observed impacts on benthic conditions

Norway has quite some experience with fish farming in deep water, and on both protected and exposed sites, but unfortunately only few of the results have yet been published, and only from protected sites (Kutti, Ervik and Hansen, 2007; Kutti, Ervik and Hoisaeter, 2008; Kutti *et al.*, 2007). Kutti *et al.* (2007) found an enriched benthic fauna despite limited or no organic enrichment of the sediments. Examination of long-term data sets indicate relatively longer time before an enrichment of the sediments is observed compared to sites at shallower depth, but over time, the sediments become enriched, when no fallowing is practiced (K. Hansen, personal communication, 2010). Since the sediments are carbon limited, they have an immediate capacity to turn over the organic matter due to the stimulation of the associated benthic organisms (fauna and bacteria) compared to coastal sediments, which respond negatively to further enrichments (Hargrave, Holmer and Newcombe, 2008). As the benthic fauna present at a given fish farm location often reflect local conditions (bottom habitat, larval supply, sedimentation regimes and connected habitat types), initial abundance, biomass and diversity may be quite different between farms (Levin *et al.*, 2001). It is therefore, difficult to generalize observations from a single study, and assimilative capacity of the sediments may vary substantially between sites. Comparison between many farms showed that the benthic fauna communities tend to change towards a more organic tolerant community and the fauna community in impacted sediments is often more uniform between farms after years of fish farming compared to initial or pre-farming conditions (R. Bannister, personal communication, 2010). The organic tolerant communities are dominated by small polychaetes such as *Capitella* spp., which is a widely distributed species (cosmopolitan), also at these depths (>50 m). *Capitella* spp. seem to generate their own environment by increasing the reduction of the sediments and increasing organic matter pools in the surface layers, resulting in high abundances of this particular species in expense of less tolerant species (Heilskov and Holmer, 2003).

At the New Hampshire (USA) test sites benthic impacts have been investigated, and factors such as biodiversity and abundance of infaunal and epifaunal communities and sediment organic buildup were used as indicators to track environmental impacts (Ward, 2004). The results showed no obvious trends for any of the univariate benthic fauna community data (density, biomass, taxonomic richness) or the ratios of pollution tolerant/intolerant taxa relative to the predicted pollution effects zones in two separate sampling periods (spring and fall). There were a couple of marginal effects with lower diversity and mean taxa numbers at one study site and it was suggested that this could be an early signal of increased organic loading to the sediment under the cages, but density and biomass increases were not observed. The densities of pollution tolerant taxa (oligochaetes, capitellids, cirratulids, ampeliscids) and pollution intolerant taxa (nuculids, paraonids, ampharetids) were calculated and compared, and pollution intolerant taxa were in the majority at all 20 study sites, with only one sample where pollution tolerant taxa represented >50 percent of the fauna. Rankings by taxa also showed very similar trends across four pollution effects zones, with spionid polychaetes and nematodes dominating in all four zones, followed by nuculid bivalves and paraonid polychaetes (both pollution intolerant taxa) in most areas for both spring and fall sampling periods. These data suggest that the benthic communities in all four zones were dominated by infaunal taxa that are relatively intolerant of organic pollution, suggesting no or only minor impacts on the seafloor. The study also calculated various ecological indices and the results showed similar values for samples from all four zones, confirming that no impacts on benthic communities were detectable. In addition, the loss-on-ignition values for spring and fall sampling of the sediments did not indicate a buildup of organic debris in the sediments.

The bottom sediments at the New Hampshire test site were also surveyed in a long-term study, and showed no seasonal or year to year variations in sediment grain size or organic matter content measured as loss-on-ignition (Ward, 2004). There was no consistent change in the organic content of the bottom sediments since the beginning of the monitoring period in 1997 until 2006 suggesting no detectable change in organic matter pools in the sediments. Videography cruises were done to track possible changes in benthic epifauna during one sampling event. Here an increase in the number of northern sea stars was found, which was partially related to cleaning of biofouling from fish cages. The organisms and organic debris removed from the cages while cleaning provide a short-term food source attracting scavengers such as sea stars. The high numbers of sea stars could also be related to a strong storm activity that occurred just before the survey. The strong bottom currents associated with a storm may have scoured the bottom causing some bivalves to be exposed, providing a food source for scavengers. The survey indicated more shell debris on the seafloor at most of the stations, which could be related to storm activity and bottom scouring. In either case, once the temporary food supply was depleted, it is likely the northern sea stars dispersed. Statistical analysis showed no significant differences in epifauna among four impact zones for both spring and fall sampling periods. Hence, no enrichment effects that occurred consistently across the impact zones were detected in the epifauna data.

In contrast to the few observations of offshore farms, studies in the off-the-coast category (Table 3) consistently show an organic enrichment of the sediments, conditioned by the dominant flow directions. Furthermore the benthic fauna is generally disturbed, but to varying extent (little or a lot) and the faunal diversity lower compared to reference sites. The benthic secondary production may well be higher, enhanced by organic matter inputs. The organic input increase bacterial production, which reduces the sediment, and the fauna found in off-the-coast sediments is more pollutant tolerant, typically dominated by small polychaetes. As an example, a study of a submerged off-the-coast/offshore farm in the Caribbean showed a weak organic enrichment in the dominant flow direction, while the benthic fauna had lower abundance under the net cages. At an aquaculture farm used for the fattening of Atlantic bluefin tuna (*Thunnus thynnus*), located at an exposed site (700 m from the coast, average bottom depth of 45 m and average current speed of 6 cm s^{-1}) in the Mediterranean Sea, Vezzulli *et al*. (2008) found no substantial differences between farm and control sites. Deviations of farm values from control values, when they occurred, were small and did not indicate any significant impact on either the pelagic and benthic environment. Deviations were more apparent in the benthic compartment where lower redox potential values, higher bacterial production rates and a change in nematode genus composition pointed out to early changes in the sediment metabolism. In addition, indigenous potential pathogenic bacteria showed higher concentration at the fish farm stations and were a warning of an undesirable event that may become established following aquaculture practice in oligotrophic environments. Other studies at shallower depth have shown more significant impact with organic matter enrichment of the sediments, increased bacterial activity, reduction of the sediments and deteriorated bottom fauna (Table 3). Water depth seems to be a key factor of the benthic impacts, modified by local production and hydrodynamic conditions.

Attraction of wild fish to off-the-coast and offshore farms may further modify the benthic impact. Studies at off-the-coast farms in the Mediterranean have shown less benthic impact due to lower rates of sedimentation (Vita *et al.*, 2004b). Similarly, Svane and Barnett (2008) found that scavengers, such as leatherjacket and isopodes, reduced the accumulation of trash feed under tuna farms in South Australia. Enrichments in the motile epibenthic fauna may on the other hand predate on the infauna and reduce their abundance and bioturbating activity (Sanz-Lazaro and Marin, 2009). Reduced bioturbation limit the exchange of metabolites and e-acceptor, which potentially accumulates organic matter due to inhibition of microbial processes like sulfate reduction. Sanz-Lazaro and Marin (2009) found accumulation of organic matter at this off-the-coast farm compared to reference sites, indicating lower decomposition capacity.

Fallowing has been used successfully for coastal aquaculture, where the sediments are left to recovery for 6–12 months (Macleod, Moltschaniwskyj and Crawford, 2006), but some sites seem to recover faster than others (Macleod, Moltschaniwskyj and Crawford, 2008). Fallowing for up to 36 months only recovered the benthic fauna community at a site, which was naturally organic rich, whereas a more oligotrophic site failed to recover probably due to the lack of organic tolerant species present (Macleod *et al.,* 2007). Fallowing for six months was also examined at an off-the-coast location, where the community structure at affected sites became more similar to communities at distant reference sites (Lin and Bailey-Brock, 2008). Additionally, a sudden disappearance of enrichment indicator species at previously affected sites during the fallow period suggested the beginnings of a recovery. However, species diversity did not increase significantly during the fallow period, indicating that the affected communities were not fully restored to pre-culture or distant reference conditions. Both studies demonstrate the potential environmental benefits of scheduled fallow periods or crop rotations in off-the-coast and possibly also in offshore aquaculture.

Sensitive habitats

Moving aquaculture further out from the coast and to deeper waters will remove the pressure on coastal sensitive habitats, but that does not mean that there are no sensitive habitats on potential off-the-coast and offshore sites. Especially off-the-coast locations will still have representation of sensitive coastal habitats, especially in areas with clear water and deep light penetration, for example in the Mediterranean Sea, where seagrasses and macroalgae are still present at 50–70 m water depths.

Hard substrate, though rare on the continental shelf, where offshore activities are planned, are the most familiar habitats to the general public due to their photogenic biota. Bedrock, boulders and cobbles can be found in a gradient of physical conditions from high to low stress. They offer a number of microhabitats, dominated by particle feeders such as sponges, bryozoa and sea squirts. Many commercially important fishes utilize boulder reefs in their juvenile stages. Soft-sediments are widespread in deeper waters (>50 m), but due to the high costs associated with studying these habitats presence of sensitive habitats is not well studied. Soft sediments are formed from finer particles such as silts and muds settling out due to reduced physical forcing, in particular in basins and sheltered sites (Levin *et al.*, 2001). The epifauna tends to be sparse in such areas with few sessile emergent species (mainly anemones and sea pens) and low abundances of mobile scavengers (Carney, 2005). In the northern Atlantic Sea the fauna is typified by burrowing megafauna that shape the surface of the seabed with burrow entrances and mounds of excavated sediment and faeces. The fauna is dominated by crustaceans, typically callianassids and in some areas with important commercial fisheries, such as the Norway lobster (*Nephrops norvegicus*) and hyperbenthic pandalid shrimps. These species are highly sensitive to hypoxia, and for Norway lobster slight changes in oxygen concentrations in the water column may negatively affect behaviour and increase mortality, which influence both recruitment and recolonization potentials (Eriksson and Baden, 1997).

Biogenic reefs are formed by mussels (oysters, mussels), polychaetes (*Sabellaria* spp.), corals and sponges. In addition to their role in transferring energy to the seabed, biogenic structures greatly contribute to marine habitat complexity by increasing the three dimensional relief of seabed topography and often have a nursery function for juvenile fishes and crustacean. As biogenic reefs are constructed primarily by living organisms, they are particularly vulnerable to physical disturbance, fishing or pollution effects associated with eutrophication. An example of deep sea sensitive habitats is from the North-East Atlantic, where the dominant reef-framework forming coral species, *Lophelia pertusa* and *Madrepora oculata*, form a symbiotic association with the polychaete worm *Eunice norvegica*, and these reefs are considered highly sensitive to anthropogenic activities such as increased sedimentation due to the delicate filtration apparatus of these corals (Dolan *et al.*, 2008). Recently large reef like formations of sponges have been found in the North Atlantic (Klitgaard and Tendal, 2004). Sponges filter particles from the water column and while small enhancement of particle load possibly is tolerable, higher loading rates may inhibit the filtration by clogging the pores.

Observed impacts on sensitive habitats

Calcified macroalgae are distributed in marine habitats from polar to tropical latitudes and from intertidal shores to the deepest reaches of the euphotic zone (Nelson, 2009). These algae play critical ecological roles including being key to a range of invertebrate recruitment processes, functioning as autogenic ecosystem engineers through provision of three-dimensional habitat structure. Calcified macroalgae contribute significantly to the deposition of carbonates in coastal environments. These organisms are vulnerable to human-induced changes resulting from land and coastal development, such as altered patterns of sedimentation, nutrient enrichment through sewage and agricultural run-off, and are affected by coastal dredging and aquaculture. It is not yet understood how interactions between a range of variables acting at local and global scales influence the viability of calcifying macroalgae and associated ecosystems. In Scotland, the movement of farms away from enclosed sites to areas with strong tidal flow has resulted in locating farms over calcified macroalgae (termed “maerl”), characterized as a habitat for a diverse array of benthic crustaceans (Hall-Spencer *et al.*, 2006). Monitoring at a farm located over a maerl bed for 12 years showed a die-back of living maerl, periods of anoxia and an accumulation of organic material on the seabed within 25 m of the cages. Assessments of crustacean assemblages showed significant reductions in biodiversity near the farm. Some scavengers (e.g. the amphipod *Socarnes erythrophthalmus*) were far more abundant near the cages than at distances >75 m from the cages, but many small crustaceans (e.g. the tanaids *Leptognathia breviremis*, *Typhlotanais microcheles* and *Psudoparatanais batei*; the cumaceans *Nannastacus unguiculatus*, *Cumella pygmaea* and *Vaunthompsonia cristata*; and the amphipod *Austrosyrrhoe fimbriatus*) were impoverished near the cages, probably due to combined effects of organic wastes and the use of toxins to combat parasitic copepods. The study concluded that farming should not be carried out at sites where long-lived biogenic habitats such as maerl occur because this will likely increase the area of habitat degradation.

Escapees and genetic interactions

Increased production of cultured fish increases the potential of huge escapes and inadvertently introductions into the wild. Compared to coastal aquaculture, off-the-coast and offshore farms are projected to increase significantly in size and being located under conditions with exposure to strong winds and high seas, the risk of release is increased. This is a challenge to the technological development, and the use of submerged cages located at depths below the immediate wave zone is one solution to reduce the risk of damage of net cages. If an escape occurs, which could also be due to attack by large predators, the release of fish to the ocean is likely to be high. One single submerged cage may contain up to 25 000 full-grown fish. Most of the current knowledge on escapees and genetic interactions is from salmon farming (Cross *et al.*, 2008). Salmon is an anadromous migrating to freshwaters for breeding and in this way quite different from most other marine fish, which have their entire life cycle in marine waters. Cultured strains interact genetically with natural populations directly by interbreeding or indirectly by modifying the ecosystem (e.g. ecological competition, spreading of disease). Cultured strains have lower fitness in the wild, and interbreeding with wild populations may thus reduce the overall fitness. In Chile, where salmon was introduced in aquaculture around 1980, escapes are found in local rivers and exert ecological and social pressures on the ecosystems and are a major challenge for the managers (Soto *et al.,* 2007; Soto, Jara and Moreno, 2001). Another example of introduced species is the oyster *Crassostea gigas*, which has caused major indirect impact upon the introduction to Europe, where it is competing ecologically with *Ostrea edulis* and *Mytilus edulis* in major estuaries in Northern Europe. For fishes, indirect interactions may decrease genetic variability and alter genetic composition of the wild stocks. The genetic interactions are considered at greatest risk when reared species outnumber the wild stocks. This is only the case for a few species, such as salmon in North Atlantic where the reared species are about two orders of magnitude higher than wild, whereas most other species (e.g. cod, bream, bass and mussels) are more abundant in the wild. Salmon is even more at risk due to the local adaptations of the strains, where genetic interactions can cause major loss of ecological performance. This risk is less for the marine species, but considering the expected increase in aquaculture production and the continuous reports on overfishing may increase the problems. Intensive culturing of seabream along the Hellenic coast in Greece has increased the landings with up to 80 percent indicating a major impact on the fisheries of this particular species in the area (Dimitriou *et al.*, 2007).

The main risks by off-the-coast and offshore farming are thus the increasing size of the farms and their exposure, increasing the potentials of major and regular losses, which has been identified as important bottlenecks for genetic impacts (Cross *et al.*, 2008). Although the farms are located farther from shore, it is still relatively close, e.g. within a few kilometres, and it virtually means that there are the same risks of direct and indirect interactions with wild fish populations as found in coastal aquaculture. Only if the farms are located in open seas, e.g. hundreds of kilometres away, interactions would be less, in particular if the farms are located away from major routes of migration and feeding and spawning grounds. Interactions with wild populations are affected by a range of factors, such as season where for example escape of salmons at the same time as the wild populations migrate to the spawning grounds have major direct (interbreeding) and indirect effects (ecological competition) on the wild fish. Interactions for seabream and seabass are less known, but are assumed to be less compared to salmon due to more abundant native populations and the lack of local adaptations, such as homing behavior for salmon. The degradation of the wild strains due to genetic interactions could be avoided by using sterile or triploid fish, and although this method is currently been developed, there are many difficulties and uncertainties to be solved for a variety of species. Only few successful examples have been provided so far.

Observed genetic interactions

In Norway, the stock of farmed Atlantic salmon greatly exceeds that of wild conspecifics (Gross, 1998). Although a relative small proportion of farmed salmon escape, the number is large relative to the population of wild salmon. In recent years, the number of farmed salmon in reported Norwegian salmon catches has been estimated to be between 30 000 and 60 000 annually (Hansen, 2006). Spawning of escaped farmed salmon in wild salmon rivers has been documented, and introgression of farmed salmon into wild populations may have negative effects (McGinnity *et al.*, 2003; McGinnity *et al*., 2004). If salmon move randomly after they escape, they may be "trapped" in the fjord system in which the farm from which they escaped is located and enter rivers within that system. This is one of the reasons that salmon farming in Norway has been restricted or prohibited in some areas close to important salmon rivers. Another reason is to reduce the risk of pathogens and parasites spreading from farmed to wild salmon populations (Bjorn and Finstad, 2002; Finstad *et al.*, 2000). Significant positive correlation between the incidences of escaped farmed salmon in the nearby rivers and the intensity of salmon farming has been found (Fiske, Lund and Hansen, 2006). As both the distance to rivers and the size of the farm are important for the encountering of escapes in natural habitats, it is only by moving to offshore location a lower pressure on wild populations can be expected. However, one third of the production of salmon occurs in areas, where it is exotic, and spawning of escapes have not been detected so far, suggesting limited genetic interactions in these areas (e.g. Chile and Tasmania [Australia]) (Thorstad *et al.*, 2008).

Disease

Diseases and virus can be both introduced and transmitted through aquaculture. Without proper controls and quarantines, it is possible for diseases or parasites to be introduced to a region through the importation of juveniles. In cases of disease outbreak on a farm, the disease can be transmitted to the wild if it is an open production system. Just as pathogens and parasites can be transferred from farms into the wild, disease free farmed species can be infected from the wild and in open production systems there is flow in both directions. Diseases can also be transmitted from farm to farm, and the salmon industry in Chile has almost collapsed due to severe virus outbreak causing the disease infectious salmon anemia (ISA). Spread of disease and virus between farms are correlated with production in a given area, and especially distances between farms and local currents are important. A relocation of farms to more exposed sites can therefore be expected to reduce the spread of disease and virus between farms. On the other hand, the increase in size of the farms may increase the risk of spreading the disease to a high number of fish, and outbreak at a single farm could have more impact. The spread of disease will depend on distances to major migration routes, and to feeding and spawning grounds, as well as the attraction of wild fish to the cages. Introduction of diseases from wild fish will depend on the wild populations and abundance of fish in the area. In a productive fishing area, the pressure will be much higher compared to less productive areas, where the last would be a typical offshore area. Disease introduction and transfer can also be a concern in shellfish and seaweed culture systems (Boyd *et al.*, 2005).

There is a range of known bacterial diseases affecting marine aquaculture, and efficient vaccines have been developed for some of them, whereas others have to be treated with antibiotics. Many bacterial strains are resistant to a number of therapeutics such as oxolinic acid, and the development of new antibiotics is an on-going process (Avendano-Herrera *et al.,* 2008). Use of antibiotics has environmental impacts, both by spreading to wild fish attracted to the cages and on the bottom habitats (Samuelsen *et al.*, 1992; Samuelsen, Torsvik and Ervik, 1992), and as the use of medicines is expected to decline in offshore farming, this risk should be minimized.

Biofouling

Marine fouling occurs globally and is a process that has always plagued mariners, whereas fish farming is a relatively young industry in comparison. Fish farm fouling is a growing, global phenomenon (Hodson, Burke and Bissett, 2000) and it is widely accepted that fouling in the aquaculture industry is an expensive problem (Hodson, Lewis and Burke, 1997). There are several positive attributes of biofouling, such as seeding mussels and filtration of the water column for particulate waste products. However, the effects of biofouling in aquaculture are largely detrimental. Hydrodynamic forces on a fouled net can be up to one order of magnitude higher than on a clean net. It can cause physical damage to the net, disruption of water flow and thereby limiting nutrient exchange and waste disposal. Indirect costs are for cleaning and repairs, and as much as US$40 000 is spent annually on removal of the fouling community from the two fish cages at the New Hampshire Open Ocean Aquaculture site (Greene and Grizzle, 2007). Removal of these organisms is necessary because of their effects on cage behavior, including the potential for causing the cages to sink. Hence, these organisms are viewed mainly as a nuisance in aquaculture. However, the fouling community potentially removes dissolved nutrients and suspended waste materials from the cages because the community includes plants and suspension feeding invertebrates.

By moving the farms to off-the-coast and in particularly offshore locations, where the nutrient availability, productivity and seed dispersal in general is expected to be lower, less biofouling can be expected. On the other hand, the increase in farm size and use of more feed, may increase biofouling intensity on the farming structures by cosmopolitan species such as barnacles and mussels. Furthermore, as the maintenance of the farms will be much more difficult and expensive and simple solutions as exchanging nets, which is done frequently in coastal farming to avoid fouling, is not possible, biofouling intensity may increase. Biofouling can be reduced by the use of chemicals, such as antifouling paints, and is probably investigated as a solution as long as negative effects on the cultured fish are avoided (Braithwaite, Carrascosa and Mcevoy, 2007).

Observed biofouling

Fouling of fish farms is influenced by number of factors, such as cage age and net texture, water depth, complexity, inclination and position in the water column. Greene and Grizzle (2007) deployed experimental nets at an open ocean fish farm in New Hampshire at different times of the year and for different durations. They found substantial and significant differences in density and biomass of the total communities of most successional sequences when comparing warmer to cooler months. *Mytilus edulis*, the blue mussel, dominated in density and biomass, and other less abundant species were amphipods (*Caprella* sp. and *Jassa marmorata*), molluscs (*Hiatella arctica* and *Anomia* sp.), the seastar *Asterias vulgaris*, and the anemone *Metridium senile*. Juveniles and adults of some species were also present in some early (1-month) successional sequences, indicating that migration may be an important process in community development. Some of the dominant species were present in all successional stages (early, intermediate and late), differing only in relative abundances in the community. The consistent dominance of *M. edulis*, and other differences in successional patterns compared to what has been typically observed for epifaunal communities in the region, were hypothesized to be the result of a combination of factors: a lack of predators such as seastars and fish that typically consume mussels in natural communities, excessive predation by nudibranchs on those species (e.g. *Tubularia* sp.) normally abundant in early successional stages, year-round availability of mussel larvae, and cage cleaning protocols that do not remove all the organisms present. The introduction of predatory fishes or seastars into or onto the cages might provide some control on the growth of fouling organisms.

Langhamer, Wilhelmsson and Engstrom (2009) studied an offshore wave power test station located two kilometres from the coast in west Sweden. Due to the depth of the foundations (25 m) and high water turbidity causing low light intensity, they found only few filamentous low-light adapted red algae. The colonization of the foundations was homogeneous, consisting of mostly barnacles and serpulid tubeworms. The primary colonization mainly comprised tubeworms and barnacles that are opportunistic and short lived. The second assemblages were more heterogeneous, and secondary colonizers, such as ascidians, had outcompeted the primary ones by overgrowing them and probably preventing them from feeding successfully. Epifaunal assemblages can form new habitats for smaller organisms (*Idotea* sp., *Jassa falcata* and *Jassa pusilla*), and constitute feeding grounds for larger predators (*Asterias* sp., *Cancer* sp.). Fish abundance was low compared to other more complex structures in shallower water in adjacent areas, probably mediated by a high abundance of *Cancer pagurus*. Lobsters were also present, but only in cavities under the foundations.

Parasites

Due to the intensity of culturing fish in cages, the risk of spreading parasites within the farm is high, compared to wild fish. On the other hand, due to the use of artificial feeds, the trophic transfer of parasites is less, although fishes farmed in net cages may become infested by parasites from wild fishes and in turn become point sources for parasites (Krkosek *et al.*, 2007; Nowak, 2007). Sea lice, copepods of the family *Caligidae*, are the best-studied example of this risk. Sea lice, the most significant parasitic pathogen in salmon farming in Europe, the United States of America and Chile, are estimated to cost the world industry US$300 million a year and may also be pathogenic to wild fishes under natural conditions. Juvenile (copepodite and chalimus) stages have repeatedly occurred on juvenile wild salmonids in areas where farms have sea lice infestations, but have not been recorded elsewhere. There is increasing evidence that lice from farms can be a significant cause of mortality on nearby wild salmon populations, but they could also infect other wild fish (Marin *et al.*, 2009). In the case of salmon, the ecological impact of parasite transmission from fish farms is mediated by the migration of wild fishes, which determines the period of exposure to parasites (Krkosek *et al.*, 2009). When the exposure period lasts for several weeks, as occurs when juvenile salmon migrate past salmon farms, it is predicted that lice accumulate to abundances that can elevate salmon mortality and depress salmon populations. High parasite loads on seaward-migrating salmon smolts have been implicated as a potential cause of high mortality at sea and reduced return of adults to rivers (Bjorn and Finstad, 2002; Bjorn *et al.*, 2007). Moving farms to off-the-coast and offshore locations is expected to reduce the infections by parasites, as least between farms, due to the larger distance between farms. Also to wild fish, in particular if farms are sited in locations away from migration routes, feeding and spawning areas.

Parasites are also a problem for shellfish farming, and Buck *et al.* (2005) found that mussels taken from offshore sites (e.g. buoys, platforms) were free of trematodes and shellboring polychaetes, suggesting reduced risk of parasite attack. Parasitic copepods only occurred at a single offshore site, on a 20-year-old research platform, but not on buoys or collectors exposed for shorter time periods. Through a variety of detrimental effects, trematodes, parasitic copepods and shell-boring polychaetes are known to affect growth performance and product quality. Buck *et al.* (2005) therefore, proposed that offshore mussel production could be a promising culture procedure because it seems to result in lower parasite burden than at traditional culture sites. Whether offshore production also results in better survival and growth, compared with inshore mussel culture on a commercial-scale, needs to be investigated further.

Wild fish attraction and predation

Coastal aquaculture farms have considerable demographic effects on wild fish by aggregating large numbers in their immediate vicinity. Dempster *et al.* (2005) found that seabream and seabass farming in Mediterranean attracted wild fish assemblages that had up to 30 different species and estimated that the aggregation biomasses ranged between 10 and 40 tonnes at five of the nine farms investigated (Dempster *et al.*, 2004). Similarly large aggregations have been noted in Greece (Thetmeyer, Pavlidis and Chromey, 2003) and the Canary Islands (Boyra *et al.,* 2004; Tuya *et al.,* 2006). Mussel rafts in the Mediterranean Sea (Brehmer *et al.,* 2003) are also known to aggregate wild fish, whereas cold water farms in the North Atlantic attract less species (Dempster *et al.,* 2009). Large aggregates of saithe have been found consistently around salmon farms showing a distinct morphology compared to natural fed species, and gadoid fish are abundant with on average 10.2 tonnes per salmon farm in Norway (Dempster *et al.*, 2009).The fish populations in the Mediterranean are dominated by a few primarily planktivorous fish, feeding on feed pellets. Also demersal fish are attracted to fish farms, although aggregations vary in numbers and species. Several observations of large predatory fish feeding on the smaller fish aggregated at the farms have also been observed. Fish farms are attractive habitats for certain species of wild fish in specific seasons, and aggregates are considered temporal stable only over weeks or a few months, although for some areas only limited seasonal variation has been found such as in the Canary Island (Boyra *et al.,* 2004). Also large spatial variability in aggregates can be found in same waterbodies for no obvious reasons (Dempster *et al.,* 2002). Adult fish of reproductive size generally dominate the assemblages, and stomach content analysis has revealed that 66–89 percent of fish consumed feed pellets lost from the cages. Wild fish may consume up to 10 percent of the pellets used at farms, indicating that food is a key attractant. High abundance of attracted fish may significantly reduce the environmental impacts of fish farming by reducing the sedimentation of waste products (Vita *et al.,* 2004b), but their own excretion of ammonium and leaching of inorganic and organic nutrients from faeces contributes to nutrient availability around farms (Fernandez-Jover *et al.,* 2007). Furthermore, increased levels of parasites and disease in wild fish are potential impacts of the dense and temporally persistent aggregations present in close proximity to large biomasses of caged fish hosting parasites and diseases (Dempster *et al.,* 2002). The presence of predator fish is less well documented, but in the Mediterranean *Pomatomus saltatrix*, the bluefish, has been observed to predate on seabream, when present inside the cages and on attracted fish when present outside (Sanchez-Jerez *et al.,* 2008).

Off-the-coast and offshore farms will most likely also attract fishes in large numbers due to the increase in size and potential increase in loss of feed pellets. This is particularly the case if the farms are located close to the shore or near to migration routes, feeding and spawning grounds. A major concern of offshore farms is the attraction of large predatory fish such as sharks and killer whales. On the Pacific coast of the United States of America and Canada, the Californian sea lion *Zalophus californianus*, the harbour seal *Phoca vitulina* and Steller and the sea lion *Eumatopias jubatus* interact with coastal fish farms by predating upon salmonids inside the cages while damaging netting in the process (Nash *et al*., 2000). On the Atlantic coast, harbour seals and the grey seals *Halichoerus grypus* cause similar problems (Nash *et al*., 2000). In Chile, negative interactions of sea lions (*Otavia flavescens*) with salmon farms have been described (Sepulveda and Oliva, 2005). Sea otters have also caused conflicts with production in specific regions (e.g. Freitas *et al*., 2007).

A final aspect of wild fish interaction is demonstrated in a meta-analysis by Ford and Myers (2008) of wild fish mortality in areas with farming compared to without. They find a surprisingly and significantly reduced survival (>50 percent) of wild fish in areas of intensive fish farming possibly explained by the environmental interactions mentioned in this review (e.g. genetic, environmental, disease). Whereas fish attracted to the cages may benefit from the surplus feed, others closely related species may suffer from intensive farming.

Chemicals and medicines

A variety of chemicals are also used in marine aquaculture, including disinfectants, antifoulants, sea lice treatments and veterinary medicines (Costello *et al.*, 2001; Read and Fernandes, 2003). Zinc, cadmium and copper have been used as tracer of feed pellets (Dean, Shimmield and Black, 2007), while copper also is used as antifoulant. All three metals accumulate under net cages, but to a larger extent than accounted for in the feed, suggesting other sources of metals (Dean, Shimmield and Black, 2007; Sutherland *et al*., 2007). The environmental impacts depend on the chemical or medicine in use. Antifouling metals, e.g. copper, tributyltin (TBT), accumulate in the sediments and benthic organisms and are transferred to the food chain. They may also affect the bacterial processes in the sediments (Mayor *et al.*, 2009) and show toxicity on the benthic organisms (Mayor *et al.*, 2008). The impacts of anti-microbial compounds can be summarized as effects on non-target organisms, effects on sediment chemistry and processes, and the development of resistance (Beveridge, Phillips and Macintosh, 1997). As discussed above, the use of chemicals as antifoulants may increase in off-the-coast and offshore farming, whereas the use of medicines is expected to decrease. The impacts of antifoulants will probably be quite similar with an accumulation in the sediments, but over a larger area due to larger dispersion. Very limited information is available on possible impacts of metal contamination of deep sea sediments.

INTERACTIONS WITH OTHER SECTORS

Current policy and spatial planning for aquaculture and other sectors tends to rely on separation and exclusion principles (Douvere and Ehler, 2009). That is, capture fisheries and aquaculture operations or wind/wave farms and aquaculture operations may be restricted to exclusive zones. Typically, such decisions have arisen out of concern for either ecological preservation or as a result of stakeholder conflicts (Holmer *et al.*, 2008). Exclusion and separation are at best partial solutions to planning challenges in the future. By addressing one or a limited number of sectors (usually those in conflict with each other) at a time, they may in fact not fully consider the range of impacts originating from the wide variety of resource uses. Moreover, they may ignore potential synergies between different stakeholders and the potential for mutual benefit.

Capture fisheries

Environmental interactions with capture fisheries expand a wide range including enrichment of habitats, increased fisheries biomass, decrease in fisheries due to negative genetic effects, damage to fisheries due to the introduction of exotic species, competition for space and fishing of fish for aquafeeds. Furthermore, certain environmental and spatial interactions are likely to vary over time or will not be evident until after a farm is established, such as changes in water quality characteristics or how commercial fisheries interact with aquaculture activities (Dempster *et al.*, 2005). Management measures may therefore, need to be location-specific and adaptive.

The environmental impact of capture fisheries has been extensively studied and its role in changing marine biodiversity, decline of wild fish stocks and interactions with other marine and coastal zone stakeholders are well described. Much of the research on the interaction between aquaculture and capture fisheries focuses, however, on uni-directional negative impacts stemming from the latter. At the stakeholder level, one of the major conflicts between coastal fisheries and aquaculture operations is on the grounds of space and regulation is on the basis of separation and exclusion. This component is considered to be of less importance when moving farms offshore. Given the evidence that aquaculture may actually stimulate fisheries at local and, in some circumstances regional level, at least in oligotrophic areas, there may be further scope for avoiding long-standing conflicts by exploiting synergies. Equally important, it will be possible to assess the relative ecological significance of aquaculture and capture fisheries operations together with other activities and tailor spatial planning accordingly. Social acceptance by stakeholders during site selection and initiation is important, and also the economic competition between aquaculture and fisheries due to the growth in scale of existing aquaculture farms, altering the balance between the two market sectors is of major concern in some areas.

The spatial location and stock alteration produced by aquaculture farms (including the catch of feed fish) may alter the harvest of the fishing vessels. In some cases, it is the same commercial fleet in the area that fishes for the feed fish for the farms during some periods of the year. This has clear implications on employment, which at the same time may alter local acceptance of aquaculture (Whitmarsh and Palmieri, 2009). In other cases, it is just the changes in the wild stock produced by increased demand for aquafeeds. However, the influence of aquaculture on the stock of feed fish also targeted by extractive fisheries may be modified indirectly by the use of more sophisticated integrated aquaculture techniques (Newkirk, 1996). Asche and Tveteras (2004) analysed the impact on wild fish stocks induced by the global demand for manufactured feed, and conclude that the problem stems mainly from open-access fisheries and that without proper management, expanded growth in aquaculture as well as other sectors using fish feed (e.g. poultry) could put additional stress on wild fish stocks by increasing the demand for feed. This aspect will be addressed further below.

Economic interactions between fisheries and aquaculture happen in different ways. From the moment of production/extraction to the exchange in the market, through the distribution logistics and future planning of the activity, fisheries and aquaculture are interrelated through several links and involve a number of different stakeholders. Beyond production of fish, the landing, transport and processing of fish from both aquaculture and extractive industries follow the same channels, and the sign of this interaction will depend on how saturated they are. The same occurs with fish promotion/marketing. The actual result of the interaction depends on the present demand for fish. The interactions between the prices of the fish from both origins and their complementary/substitutive nature depending on their quality and seasonal availability are also important aspects. An additional interaction exists in the labour market, where qualifications needed for fisheries and aquaculture may be complementary. The establishment of new aquaculture farms also increases the financial risks of the traditional fishery sector, as they may compete for limited subsidy resources (Gibbs, 2004).

Wind and wave farms

The idea to combine new emerging industries, such as offshore wind farms and marine aquaculture, within the same ocean territory may provide an opportunity to create multi-purpose marine areas. Besides integrating conflicting demands, this might also yield substance for policy options and future strategies beyond the national level. Naturally, multiple uses are closely interconnected in that the activities of one group influence actions by other user groups. The interacting groups have to somehow cooperate with each other and find suitable management forms in order to avoid adverse impacts associated with the multiple-use counterpart. In natural resources management, negotiated agreements and other legal or informal arrangements between different groups and various levels of governments have attracted considerable attention as a management alternative that contributes to social and economic mainstay of sustainability. Some of the greatest benefits attributed to cooperative management are characterized as task allocation, resource exchange, linkage of different types and levels of organization, reduced transaction costs, risk sharing and conflict resolution.

Along coasts with plans or existing wind and wave farms, the observed high spatial competition of stakeholders has encouraged the idea of integrating open ocean aquaculture in conjunction with offshore wind farms beyond the 12 miles zone. The cultivation of seaweeds and blue mussels is biologically and technically feasible in a high-energy environment using modified cultivation strategies (Buck *et al.*, 2008). The point of departure of a proposed multi-use concept is that the solid groundings of wind turbines or wave farms can serve as attachment points for the aquaculture installations and become the key to the successful commercial cultivation of any offshore aquatic organism. However, spaces in between the turbines are also attractive for farming projects, since public access is restricted and thus, the cultivation site protected from outside influences. An economic analysis of different operation scenarios indicates that the market price, the annual settlement success of juvenile mussels and availability of food are the main factors that determine the breakeven point for mussel farming and as operational costs are for fish farming. Social and policy science research reveals that the integration of relevant actors into the development of a multi-use concept for wind/wave farms and aquaculture interaction is a complex and controversial issue (Buck *et al.*, 2008). Combining knowledge and experience of wind/wave farm planners, as well as mussel fishers and aquaculturists within the framework of national and international policies will be the most important component for designing and developing an effective offshore co-management regime to limit the consumption of ocean space.

Exploitation industries

The exploitation of oil, gas, sand, gravel and mining potentially interacts with offshore farming. For instance, the United Kingdom oil and gas exploitation activities take place in the North Sea, which is a potential site for offshore farming. However, as the actual space used by fish farms is relatively small, it should be possible to accommodate fish farming along with exploitation activities. As with the wind and wave farms there is a potential of sharing resources when combining exploitation and offshore farming, such as ships and landing facilities, which could be of mutual benefit for both users. Fish farming in connection with abandoned exploitation facilities (e.g. old oil rigs) has been proposed as a possible solution to solving some of the technological constrains of offshore farming and thus lowering the development costs of offshore farming. Regulation, as will be discussed below, is probably one of the most critical concerns to solve issues among multi-users of this zone. Fish farms have to be located at a safe distance from possible sources of contamination, such as oil spills and chemical hazards.

Maritime transport

Offshore farming interacts with the maritime transport for siting of farms. It is necessary to place the farms away from intensive shipping routes, such as the international traffic routes along coast lines and across oceans. There are certain areas with intense maritime transport such as the English Channel and Strait of Gibraltar, where establishment of offshore farms should be prohibited or strictly controlled. The actual area used by fish farms is small, and by proper planning of offshore siting, e.g. by confining the farms to certain zones of production activities, it should be possible to avoid conflicts with maritime transport. It is now possible to secure the farms through various remote alarm systems used in modern navigation, making the farms visible to the ships, independent of weather conditions, sight and wave activity. The most difficult conflicts are probably with active fishing fleets, and it can be argued that farms should be placed outside intensive fishing areas or in reserves within the fishing area. Specific interactions with fisheries have been discussed earlier in this review.

ECOSYSTEM ISSUES

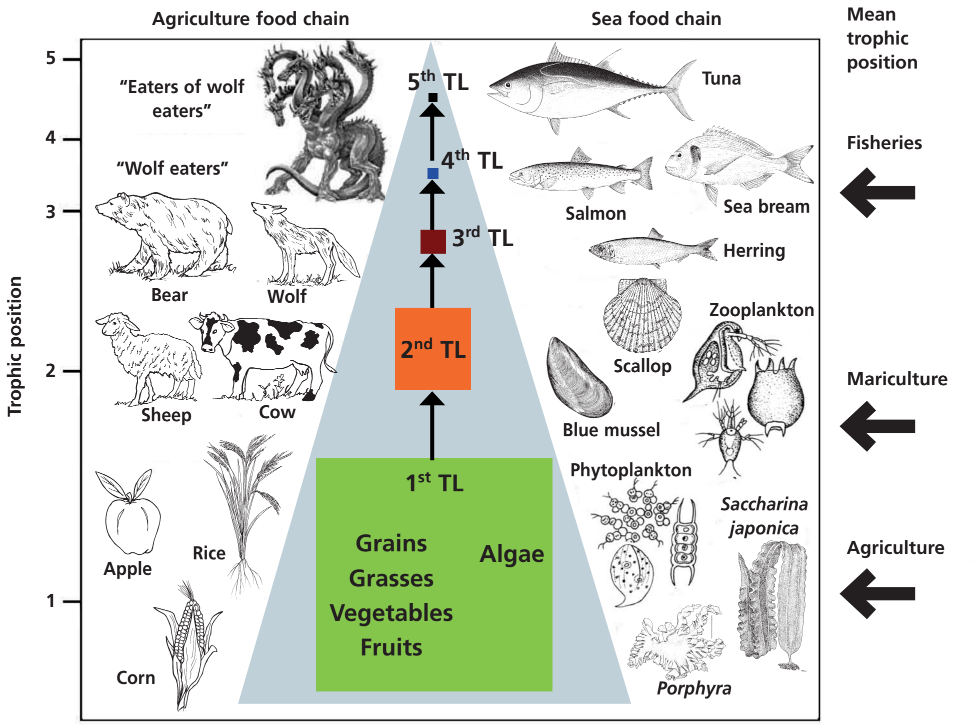
Ecological foodprint (feed resources)

The feed resources used for off-the-coast and offshore farming are considered to be the same as in coastal aquaculture, undergoing the same development as in coastal aquaculture, where the feed is constantly modified for improving the economic output of farming (Asche, Roll and Tveteras, 2009). It is possible that offshore farming will require some optimization with respect to the physical conditions (e.g. sinking rates, breakage, conservation), but as the same species are considered to be cultured, the overall composition of the feed pellets is expected to be quite similar. The composition of feed pellets are currently developed to contain a larger fraction of terrestrial derived compounds to minimize the pressure on fish meal and in particular fish oil, which is near its exploitation limit (Duarte *et al*., 2009). At present, small pelagic forage fish species such as anchovies, herring, mackerel, sardines, etc., represent the largest landed species group in capture fisheries (27.3 million tonnes or 29.7 percent of total capture fisheries landings in 2006 (Tacon and Metian, 2009a; Tacon and Metian, 2009b). They also currently constitute the major species group actively fished and targeted for nonfood uses, including reduction into fishmeal and fish oil for use within compound animal feeds, or for direct animal feeding; the aquaculture sector alone consumed the equivalent of about 23.8 million tonnes of fish (live weight equivalent) or 87 percent in the form of feed inputs in 2006 (Tacon and Metian, 2008; Tacon and Metian, 2009a; Tacon and Metian, 2009b). The main pressure from development of off-the-coast and offshore farming is thus not specific demands, but more the quantity of fish feed expected to be used by the prospected increase in production volume (Duarte *et al.*, 2009). The efficiency of feed use in off-the-coast and offshore can be argued, some suggest at lower efficiency due to the larger loss under the more difficult production conditions (e.g. less precise feeding in larger farms, increased dispersion of fish feed), whereas others proposed more efficient feeding due to less disease and increased welfare for the fish in larger cages and higher water exchange rates in the cages. Various solutions to high ecological foodprints in fish farming have been proposed such as introducing integrated multitrophic farming (see below); change from marine to terrestrial sources of feed, using macroalgae or mussel meal instead of small fishes and lowering the trophic chain in aquaculture (Figure 3) (Duarte *et al.*, 2009).

Carbon footprint

Compared to most other animal husbandry practices, aquaculture has a small overall CO_2 carbon footprint (Bunting and Pretty, 2007). This is particularly the case for freshwater herbivorous or omnivorous species such as carp, requiring at most small amounts of fertilizer, often organic, and in some cases, low-energy supplementary

FIGURE 3
Comparison of trophic chains within the agriculture (left) and seafood chain (right). Currently mariculture has a trophic position of 1.7 due to intensive algae and shellfish culture in China, compared with 3.5 in salmon and seabream farming



Source: Modified from Duarte *et al*., 2009.
Note: All line drawings by Manuela D'Antoni, FAO.

feeds, although high feed conversion rates (FCR) for some species such as tilapia has negative impact on the carbon footprint (Table 4). In contrast shrimp, salmon and marine carnivores, due to their high feed energy or system energy demands, have very high footprints. However, as farmed aquatic organisms do not themselves emit methane, such as observed for livestock, it reduces the total carbon footprint per tonne. Off-the-coast and offshore farming, compared to coastal farming, increase the carbon footprint due to the fuel costs for increased transportation of feed and fish. As in all food production sectors, post-harvest activities entail stocking, packaging and transporting and they create post-consumption waste, all linked with CO_2 emissions. In this case, off-the-coast and offshore production is not considered to differ from coastal farming. Of special note of CO_2 emissions are those related to air transport. Intercontinental

TABLE 4
Energy use in aquatic farming systems compared to agriculture

	Industrial energy consumption (GJ t^{-1})
Semi-intensive shrimp farming	169
Grouper, sea bass cages	95
Carp, intensive recycle	56
Salmon cages	56–105
Trout ponds	28
Catfish ponds	25
Carp ponds, feeding and fertilizer	11
Pork[1]	16
Beef[1]	40

[1] De Vries and de Boer (2010)
Source: Bunting and Pretty, 2007.

airfreight may emit 8.5 kg CO_2 per kg of fish shipped, about 3.5 times the levels from sea freight, and more than 90 times those from transport of fish consumed within 400 km of its source. Product form will also have an important effect, including energy embodied in packaging, and can influence options for maintaining quality and value with respect to transport method. As the same species are considered to be produced in off-the-coast and offshore farms, it is not likely that CO_2 emissions of post-harvest activities will change significantly. Tuna farming should be mentioned as a particular carbon costly production due to the use of air transportation of fresh fish.

Environmental costs

There are environmental costs associated with every form of food production, including aquaculture and none of these appear sustainable at the present time (Brooks, 2007). It has been obvious for several decades that the food resources in the oceans are being over-exploited and few jurisdictions have been successful in managing the harvest of fish and shellfish. Whereas small-scale aquaculture is an ancient practice, industrial-scale aquaculture is relatively new and because of its scale, it can potentially carry significant environmental costs which must be managed to ensure that they do not become widespread or irreversible.

As discussed in previous sections, environmental effects on water quality and pelagic food webs are considered to be less severe compared to the benthic environment. For coastal salmon aquaculture in the Northeast Pacific, Brooks (2007) found that significant effects on the benthic environment to be restricted to a few hectares within 200 m of net cages, which is consistent with findings for coastal aquaculture in general. He found, that biogeochemical remediation of the sediments at reasonably well sited farms took 6–12 months. In the worst case studied, biogeochemical remediation was nearly, but not totally, complete following five years in fallow. Biological remediation occurred within one year following completion of biogeochemical remediation. The measured reductions in the biomass of benthic invertebrates due to organic enrichment resulted in the loss of approximately 300 kg of wild fish during production of 2.5 million kg of Atlantic salmon, which can be considered a relatively minor impact. In contrast Diaz-Almela *et al.*, 2008, found loss of the sensitive seagrass *Posidonia oceanica* in the Mediterranean, which can be considered an almost irreversible change due to the slow recolonization potential (hundreds of years). Under off-the-coast and offshore conditions, organic enrichment is considered to be less, and if sensitive habitats are avoided, production could possibly proceed longer on a single site before fallowing is required to recover the sediments biogeochemically and biologically. On the other hand, biogeochemical and biological remediation may take longer at deeper sites, as discussed in previous chapters, and thus increasing the environmental costs. Compared to producing an equal amount of beef, the small (1.6 ha average) and short-lived (44 month-long) effects created by salmon farming, is negligible. For comparison production of equal amounts of beef requires 6 982 ha of high quality pasture for 30 months plus as long as several hundred to a thousand years of remediation. Brooks (2007) also concluded that for achieving sustainability it is necessary to prioritizing the costs of all forms of food production and focusing on solving the most important and tractable issues first. For instance, bycatch and lost fishing nets and pots waste a significant portion of the ocean resources each year. From a sustainability point of view, these costs represent a far greater hazard to marine life than the lost production under a salmon farm.

Carrying capacity

Carrying capacity of off-the-coast and offshore farming is considered to be higher due to the dispersion of particulate waste products minimizing the benthic impacts. It is, however, important to consider the lack of scientific evidence behind these expectations. Due to the lack of knowledge on impacts of organic enrichment in deep sediments, including studies of fallowing times required for re-establishment of the biogeochemical and faunal conditions in the sediments, it is difficult to predict carrying or assimilative capacities at offshore locations. There is a need of experimental studies and monitoring efforts under off-the-coast and offshore conditions along with modelling of organic enrichments, e.g. as done for coastal aquaculture, where several models of benthic impacts are available. As deep sediments are generally considered to be carbon limited, they are expected to be able to take up significant amounts of organic matter, but as this organic matter differs widely (e.g. amount and composition) from the organic matter usually settling in deep systems, both the biological and biogeochemical response of deep communities may turn out different than expected. Benthic communities, low in abundance, diversity and biomass, may be quite sensitive to organic enrichments, in particular if the organic matter load exceeds the capacity of the community to consume the organic matter (Gallucci *et al.*, 2008). In such a case, the microbial processes are stimulated, and potentially reducing the sediments and eliminating less pollutant tolerant species. It could well be a large fraction of the benthic fauna as they are adapted to carbon starved conditions rather than organic rich, anoxic and sulfidic sediments. It is likely the recovery of deep-sea habitats will occur, but it will probably take longer, especially as many deep-sea species have slower growth rates, later sexual maturation and variable or infrequent recruitment (Levin *et al.*, 2001).

REGULATION AND MONITORING

The legal and regulatory environment surrounding the offshore aquaculture industry is cited consistently as one of the major hurdles to its development (Fletcher, 2003). Individuals interested in developing sustainable offshore aquaculture face challenges in the form of a fragmented and often inconsistent permitting process among the international, national, and local agencies and questions regarding leasing, siting and property rights. The lack of adequate leasing options restricts the feasibility of moving farms offshore. One avenue to sustainable offshore aquaculture is the consolidation of specific sites for aquaculture leases. Marine zoning faces significant challenges that its land-based counterpart does not, such as boundary disputes, enforcement difficulties, and more frequent user conflicts. Coastal and offshore waters represent a public resource for use by fishers, recreationalists, mineral exploiters, and the shipping industry. Despite significant policy conflicts, coastal managers across the globe are recognizing the importance of setting aside particular areas of marine waters for specific uses. These include marine sanctuaries; areas used as military zones; specific lease areas for offshore oil and gas exploration; and, state and federal "marine reserves" or "marine protected areas" to conserve fish and other marine resources. There is still much to learn about the deep sea, making comparisons with existing coastal protected areas difficult. One suggested solution is the development of a marine reserve network extending throughout coastal areas and the high seas (Houde and Roberts, 2004). Networks of protected areas could protect highly migratory species, and may even protect undiscovered habitats such as those associated with seamounts. Another potential mechanism to protect migratory deep-sea species could be mobile reserves that would follow sensitive species along migration routes. In the deep sea, potentially the most immediately effective measure would be to allow aquaculture production in areas where fish stocks have reduced and benthic damage already occurred but to close other areas to new fishing to protect existing fish stocks and benthic habitats.

When farms have been established on off-the-coast or offshore locations, it is important to monitor the farms to follow-up on the environmental impacts. Monitoring of off-the-coast and offshore locations is constrained by the water depth and the high cost of operation under such conditions. Furthermore, the lack of scientific knowledge on possible impacts makes monitoring further cumbersome. Water quality parameters are possibly easier to follow, as there are already now various techniques for remote sensing of water column parameters (temperature, oxygen, nutrients, fluorescent), and loss of feed and faeces can be monitored by videography and deployment of sedimentation traps. The main problem is the benthic impacts, at potentially deep locations (50 to several hundred meters). Remotely operated vehicles (ROVs) can support collection of benthic samples by visually inspecting the sediment surface, but sampling has to be undertaken to study the organic enrichment and fauna communities. There is still a lack of consensus on monitoring of aquaculture farms in coastal areas (e.g. Borja *et al.*, 2009; Holmer *et al.*, 2008), and even less is known about the benthic response of off-the-coast and offshore locations. In the EU-funded Ecosystem Approach to Sustainable Aquaculture (ECASA) project, Borja *et al.* (2009) found that indices based on benthic fauna showed contradictory responses in several indicators (individual abundance, biomass), whereas a more consistent response was found when applying indices (Infaunal Trophic Index [ITI] and AZTI's Marine Biotic Index [AMBI]). They demonstrated that the environmental variables were explained by the variability in the macrofaunal variables (up to 53 percent), while the remaining variance was divided among three groups of variables: (i) hydrography (12 percent, depth, distance to farm, average current speed); (ii) sediment (5 percent, Eh and percentages of silt and total organic matter); and (iii) cages (15 percent, years of production and annual production). They suggested the use of several benthic indicators/indices in assessing farm impacts, together with the investigation of dynamics of the studied location (water depth, years of farm activity, total annual production), to be able to interpret the response of benthic communities to the organic enrichment from aquaculture. These suggestions are already much more detailed than undertaken at most coastal farms at present, and due to the larger area of dispersion of waste products at offshore farms, such analysis will be operationally demanding. Similar monitoring programmes, slightly less detailed, are already in use in Norway, Scotland and Canada. e.g. by using the Modelling-Ongrowing Fish Farms-Monitoring (MOM) protocol (Ervik *et al.*, 1997; Hansen *et al.*, 2001; Wildish, Hargrave and Pohle, 2001), and could be adapted for use in off-the-coast and offshore locations. Modelling of the dispersion could be a tool to focus the sampling efforts in spatial and temporal dimensions.

OTHER ISSUES

External factors

At the moment, climate change is actively working as an external forcing factor on marine aquaculture, as the suitable areas of farming are expanding into the Arctic due to reduced ice cover and increased production period during summer. Hardly any information is available on the fate of waste products under Arctic conditions. Both the pelagic and benthic communities are quite productive, when they are not limited by light or carbon input, and it is likely that they can accommodate inputs of dissolved nutrients and organic matter, but research should be done to explore the fate of waste products in the Arctic along with increasing temperatures and light availability. Climate change may also affect aquaculture production at lower latitudes, as the production season may be prolonged due to higher water temperatures during winter, which may increase the nutrient and organic load compared to existing conditions and affect the carrying capacity of sites. Carrying capacity is often based on an annual production following a seasonal growth pattern with low feeding during winter. Also, higher summer temperatures may affect aquaculture production, but more likely in a negative way, as for instance salmon and rainbow trout do not tolerate high temperatures well and decrease feeding during warm temperatures. Intensive weather events, such as increasing storm frequency and harmful algae blooms (HABs) may also negatively affect aquaculture production by increasing the risk of damage to the farm installation and reduced water quality in the farms leading to mass mortality.

Economy is an important driver of marine aquaculture and some will say the most important driver (Asche, Roll and Tveteras, 2008). Off-the-coast and offshore farming have been proposed now for many years, over a decade, and in particular offshore farming seems to develop slower than proposed. Investment costs and fluctuating market sales are some of the drivers of offshore aquaculture production. The environmental pressure on offshore locations will depend on the degree of expansion into the offshore zones and the need to consider only a few farms or like in Norway >50 percent of the aquaculture production as off-the-coast/offshore. The investment costs are likely to decrease as the sector expands, whereas operational costs may be constant or even increase due to increased price for feed, labour and energy use. The market situation is strongly dependent on the public perception to fish products and aquaculture production, but as the capture fisheries will not be able to feed a growing human population, it is likely that the demand for healthy seafood to the wealthier part of the world will increase significantly in the near future. At present, the economic crisis of the Western world has decreased the demand for seafood, and it is only due to the collapse of salmon production in Chile, that the price is kept high for farmed salmon. Prices on seabream and seabass have also declined.

Integrated multi-trophic aquaculture

Ecologically friendly aquaculture crops, such as seaweeds, herbivores, omnivores, and detritivores can be cultured using relatively less of our limited natural resources and produce relatively less pollution (Neori, 2008). They also top FAO's estimates of aquaculture crops for the 21st century. These crops already comprise nearly 90 percent of global aquaculture tonnage, >90 percent of all aquaculture production in China and >60 percent of production even in North America. Consumers prefer them, most likely due to their low prices. It is therefore important to consider these principles also in off-the-coast and offshore aquaculture. It has been proposed that current monoculture practices and perceptions intrinsic to the aquaculture industry can be turned around into a sustainable profitable expansion of carnivores production with organisms lower in the food web in ecologically-balanced aquaculture farms (Duarte *et al*., 2009). Both blue mussels (*Mytilus edulis*) and macroalgae (brown seaweeds) have shown potentials when tested in the North Sea (Buck *et al*., 2008) but food availability for the mussels and physical conditions for both types of organisms need to be considered for each specific site. Species should be selected based on their ecological functions in addition to their economic potential under off-the-coast and offshore conditions. Particularly, the "cleaning aspect" of integrated multi-trophic aquaculture (IMTA) has to be considered, as waste products are dispersed rapidly and the filter effect by mussels may be constrained under offshore conditions. Low concentrations of "natural food" in the form of dissolved nutrients for macroalgae and phytoplankton for suspension feeding mussels have to be considered, as the growth rates may be too low to obtain an economically efficient production. Growth experiments with *M. edulis* in an offshore setting with high currents show that the mussels stay closed during strong current, limiting their growth rates at the low food availability (H.U. Risgaard, personal communication, 2010). Also growth of the brown macroalgae *Saccharina saccharias* was nutrient limited and had suboptimal growth rates for a significant part of the growth season (M. Birkeland, personal communication, 2010). Molluscs and seaweed farming has been proposed together with wind and wave farms, where they can benefit from existing structures and possible shelter as discussed in a previous chapter. The experience with an offshore aquaculture farm of *Laminaria saccharina* conducted in 2002 assessed the maximum hydrodynamic forces affecting farmed algae (Buck and Buchholz, 2005). The researchers tested *Laminaria* in tanks and found that neither did measured nor calculated values of drag exceed those forces of wind or current, provided the algae had been gown in a current >1 m s^{-1}. Even in storm conditions with maximum current velocities of 1.52 m s^{-1} and wave heights of up to 6.4 m can cultivated *L. saccharina* withstand the high energy environment.

Furthermore it is important to mention that governments have the tools to reward IMTA principles by means of tax credits and nutrient credits and to penalize unbalanced monoculture approaches by means of "polluter pays" fines, thereby providing IMTA farms with a significant economic advantage. Such measures are under investigation in several countries, and already in use for agriculture purposes in Sweden, where mussel cultures remove diffuse load of nitrogen from agriculture production (Lindahl *et al.*, 2005).

Research and development needs

As the knowledge about environmental interactions is very limited for the off-the-coast and offshore farms there are large research and development (R&D) needs within this field. This is particularly the case for the benthic effects due to organic enrichment, as the few studies available indicate organic enrichment also at off-the-coast and offshore farms. Studies are also needed for the water column, where there is little knowledge about effects of released dissolved nutrients and organic compounds under more oligotrophic conditions compared to coastal locations. Since environmental interactions depend on the farm production, such as size, species, location and feeding techniques, it is important to link surveys of environmental conditions at existing farms with experimental studies to clarify existing combinations of production and environmental conditions. In addition, numerous other factors such as the importance of attracted fish around the cages and their modification of environmental effects, the use of chemicals and medicines and their distribution in the environment, the risk of escapees, should be considered as R&D needs.

With respect to the discharge of nutrients to the water column, it is important to investigate their fate in the environment, especially in periods when production is not limited by light. There is a possibility that nutrients are transported up the food chain and contribute to changes in trophic relationships. Release of dissolved organic matter may stimulate bacterial production, and the fate of this pool of organic matter may be relevant to both the oxygen conditions in the water column and the regeneration of nutrients and coupling to higher trophic levels.

In the benthic environment a key element to consider is the carrying capacity of the sediments and how will it be affected by the addition of organic matter of a different quality and quantity compared to natural systems. Knowledge of benthic fauna response to organic enrichment is not known as well as the restoration of fauna community after a possible modification due to organic enrichment. This has implications for fallowing principles. Also sensitive benthic communities and their response to organic enrichment are largely unknown.

For both off-the-coast and offshore farms there are a number of new production methods intended to be used. One example is submerged cages, which are lowered below the wave depth and thus are closer to the sea bottom. Due to the challenges of anchoring at large depths, floating net cage systems are tested, which can reduce the overall loading of waste products at a specific site, but spread the waste products over larger areas. Finally, farms located along with other types of farms (wind/wave) are also new with many new types of interactions, which can be envisaged.

Hydrodynamics are expected to differ much in off-the-coast and offshore farms. Basically the farms are more exposed and a larger dispersion of waste products, which may make it difficult to monitor farms in a controlled manner. Furthermore, complex coastal and ocean currents, and their variations over seasons lead to complex situations. Stratification of water masses and tidal effects can also contribute to complex sedimentation conditions, which makes it difficult to examine both near-field as far-field effects.

An important environmental aspect of the off-the-coast and offshore farms is locating far from land, increasing the energy consumption for maintenance due to increased transport. It is, therefore, essential to develop alternative energy supplies for farms, for example in the form of wind, wave and solar power to supplement the farms with energy and reducing carbon footprint.

IMTA principles are well established in many tropical fish farming systems, but are still in their infancy in coastal aquaculture, and limited experience is available for off-the-coast and offshore farms. It is therefore necessary to explore first the environmental impacts of IMTA and analyze the environmental benefits. Specifically, it is necessary to examine how coupling between different trophic levels and sufficient high growth rates can be achieved under the often more nutrient-poor conditions under off-the-coast and offshore conditions. Also it will be important to understand the fate of waste products in the Arctic and Antarctic during a climate change scenario, as well as interactive impacts of nutrient and organic matter loading of pelagic and benthic systems along with increases in temperature and light availability.

There is an urgent need for a consensus around the monitoring of marine aquaculture worldwide. Several of the major producer countries apply fairly comprehensive monitoring programmes, whereas monitoring is more sporadic in many other countries. There is a need for a proliferation of existing knowledge from the well-established programmes, as well as an adaptation to new conditions for the off-the-coast and offshore conditions. This is particularly true with respect to the use of larger farms, the significance of an increased water column and deeper sediments. Monitoring programmes must be adapted in terms of spatial and temporal scales, and development of remote sensing equipment (e.g. loggers, surveillance cameras) and monitoring equipment for deep water (e.g. ROV) is required.

Mapping of habitat and hydrodynamics. It is necessary to get a much better understanding of benthic communities at the proposed sites. The benthic habitats are poorly described specifically for offshore sites, where there is limited knowledge on the distribution of sensitive habitats such as maerl, sponge and cold water corals. As hydrodynamics are considered so important for off-the-coast and offshore conditions, it is important to have good description of local hydrodynamic conditions which may affect the farming conditions.

CONCLUSION

Based on this review, the predictions for environmental interactions of offshore compared to off-the-coast farming are summarized in Table 5. The most important interactions in offshore are those related with visual impacts, benthic flora, wild fish and use of fish as feed. Of these four issues, the visual impacts and negative impacts on benthic flora are expected to disappear by moving offshore. Interactions with wild fish are expected to be reduced, whereas the use of fish in feed will remain unchanged. Similarly most other interactions are expected to be reduced or remain unchanged by moving the farms offshore, and as such environmental benefits can be expected. This is particularly the case, if farms are placed at locations with high degree of exposure and erosion bottoms, increasing dispersal beyond the biological response time for uptake of waste particles.

Major gaps of knowledge are related to mapping of the deep seafloor and sensitive habitats. Experimental evidence of organic matter enrichment is needed to understand the assimilative capacity of deep sea sediments, as well as the response of the infauna to fallowing. Finally, relations between cultured and wild fish with respect to genetic, disease and parasitic interactions need further examination before farming offshore can be recommended.

TABLE 5

Environmental impacts of mariculture in off-the-coast locations and predictions for offshore locations. Impacts are categorized as "low" (barely detectable), "medium" (enrichment/ detectable), "severe" (negative impact) and predictions at offshore as "lower", "no change" or "higher" impact compared to off-the-coast

Impact	Observed off-the-coast	Prediction offshore
Water quality (nutrients)	Low	Lower
Carbon footprint	Low	Higher
Enrichment sediments	Medium	Lower
Sediment microbial activity	Medium	Lower
Invasion of exotic species	Medium	Lower
Wild fish (disease)	Medium	Lower/no change
Benthic fauna	Medium	Lower/no change/higher
Wild fish (attraction)	Medium	No change
Fisheries	Medium	No change
Use of antifoulants/chemicals	Medium	No change/higher
Escapees (incl. spawning)	Medium	No change/higher
Visual impacts	Severe	Lower
Benthic flora	Severe	Lower
Wild fish (genetics)	Severe (salmon)	Lower/no change
Use of fish as feed	Severe	No change

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Sustainable development of marine aquaculture off-the-coast and offshore – a review of environmental and ecosystem issues and future needs in tropical zones

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ABSTRACT

The ecological impacts of intensive tropical coastal mariculture have reduced its potential for expansion. The increasing opposition to projects such as shrimp farms and the eutrophication of coral reef habitats in the tropics is among the chief incentives driving offshore operations. Tropical off-the-coast and offshore mariculture is a growing industry with considerable economic and ecological potential. However, its growth in the tropics will require a major allocation of capital, knowledge and planning resources to tropical nations, most of which are poor, underdeveloped, lack infrastructure and are distant from target markets. Hence, the benefits and costs of off-the-coast and offshore farms in tropical regions are not directly comparable, since extensive pond aquaculture and other low-tech production systems benefit the rural poor, whereas offshore mariculture is currently restricted to corporate initiatives which have the capacity for large capital investment, import of technology and assumption of significant risks. Individual offshore farmer ownership and operation in the tropics is therefore still a substantial socioeconomic challenge due to the large initial investment required. While the warm climate regime between the tropics of Cancer and Capricorn offers numerous advantages and potential for the cultivation of various marketable species, these are different to the species reared in temperate offshore farms. Whereas this may appear to be a trivial point, it is essential to note that the high cost and capital investment involved in offshore mariculture dictates the production of high-value species intended for export to the rich developed world. Most offshore projects have thus, focused on high-value predator species such as cobia, snapper, amberjack, seabream, red drum, pacific threadfin, seabass and tuna.

Unlike coastal aquaculture, tropical off-the-coast and offshore are not limited by site availability but rather by availability of capital, technology and expertize. Two regions, namely the Far East and the Caribbean/USA-Hawaii, have recently emerged as geographic epicentres of tropical and offshore aquaculture development. Off-the-coast and offshore aquaculture in the Far East is dominated by China (and is mirrored by Viet Nam and Taiwan Province of China) which has achieved commercial production levels. Operations in these nations are driven by substantial national subsidies, lucrative fish prices from regional markets, limited coastal space, and are estimated at 500 000 tonnes. Over 60 species have been tested for tropical off-the-coast and offshore culture in both sea-worthy and submersible farming systems in China. Most systems are either imported from Norway or adapted (from existing designs) and developed locally; focusing mainly on cobia and amberjack as the most abundantly cultured species, alongside flatfishes, seabreams and a host of other species, most of which are native to the tropics. On the wake of the boom in off-the-coast and offshore production in China neighbouring tropical countries, such as Viet Nam and India are actively joining this industry as well.

The second epicentre for off-the-coast and offshore farms is largely U.S.-sponsored and lies in Hawaii (USA) and the Caribbean, with additional projects planned for tropical South and Central America. It differs from the Asian experience mostly in the small-scale (most operations are still in experimental phases, with low total production), source of funding (predominately private sector), and the low number of cultured species, although here too emphasis is being placed mainly on cobia. Furthermore, these operations often focus on development of technology, rather than on commercial production.

Isolated, small-scale attempts at off-the-coast and offshore aquaculture production have been reported in Oman, the United Arab Emirates and elsewhere, where Mediterranean-like operations of seabream culture were conducted. Other tropical regions such as Africa have coastal aquaculture operations, but no offshore activity, with the exception of European sponsored efforts in the islands of La Reunion, Mayotte and Mauritius.

While offshore mariculture is more costly, risky and logistically difficult, properly planned offshore facilities can avoid many of the environmental problems of sheltered (coastal) systems while maintaining high production levels. Indeed, a number of tropical projects, mainly in China today, explore the feasibility of polyculture and integrated aquaculture systems in highly-exposed sites. Moreover, several operations have started to experiment with offshore systems for growing pollution-mitigating complimentary species, such as shrimp, scallop, sponge and mussels. This departs from the majority of aquaculture in developing tropical nations, which is dominated by production of shellfish, shrimp and seaweed for export, as well as freshwater carp, milkfish and tilapia intended for local consumption.

The main challenges identified for development of off-the-coast and offshore mariculture in the tropics include:

1. The need to lobby for development, which should address permitting, financing and government subsidy issues.
2. The need to select species on the basis of trophic level, with preference for herbivorous fish, shellfish and algae.
3. The need for site selection criteria, favoring sites with good flushing rates to maximize fish health, and highlighting the need for: proximity to hatcheries, processing plants, markets and distance from ecologically sensitive areas or other farms.
4. The need to balance distance from shore with ecological impact, carbon footprint/tourism/NIMBY/distance traveled by farm workers.
5. The need to develop protocols for environmental monitoring and farm management.

INTRODUCTION

The ever growing demand for food from the sea has led to heavy exploitation of wild marine stocks. Dwindling oceanic stocks and marine fishery yields have prompted mankind to rely today more than ever on aquaculture. As a result, there has been a notable surge in aquaculture, with an annual increase of almost nine percent per year since 1970 (WHOI, 2007). Aquaculture has also shown considerable growth in the tropics in recent years (Troell, 2009) and especially in China (Halwart, Soto and Arthur, 2007).

Despite the abundance of rains, ample sunshine and warm temperatures that characterize the tropics (i.e. potentially rich food webs and high production rates) they are home to some of the poorest countries in the world (de Silva, 1998). The industry that many associate with tropical aquaculture is that of shrimp farming in earthen ponds, since this practice showed an exponential growth in the 1980s, but that is changing radically in recent years. Although basic physical conditions may be similar throughout the region, most tropical aquaculture takes place in Southeast Asia and South America, whereas very little exists along the coasts of Africa. This disparity is probably related to the physical features of the coastline and lack of expertise and capital (needed for investment), but is probably also related to cultural and social differences.

Whereas mariculture can provide a solution for the huge demand for aquatic food and products, it relies and impacts on many marine resources. There are numerous issues that cause concern among stakeholders in the coastal zone with regard to aquaculture, including:

- visual pollution;
- pollution of the water column with farm effluents;
- modification of coastal and benthic habitats (e.g. mangroves, coral reefs);
- creation of benthic anoxic zones due to deposition of waste feed and faeces;
- feed and seed from wild stocks;
- transmission of disease from cultured to wild fish;
- escapees interbreeding with native animals of the same species and reducing genetic diversity in the local population;
- use of antibiotics;
- noxious odors;
- excessive noise;
- interference with navigation;
- interference with fishing;
- introduction of exotic species; and
- interactions with threatened or endangered species.

In addition, there are global-scale or ecosystem-wide issues such as the need for fishmeal/fish oil to feed fish, destruction of essential wetlands such as mangrove forests, etc.

In general, there is a huge demand for space in the coastal zone and competition among stakeholders is fierce. The list of coastal stakeholders (defined as individuals or organizations who have a direct and/or indirect interest in the area) is long and as a newcomer to the coast (coastal aquaculture is one of the newer industries in coastal areas), aquaculture is at a clear disadvantage relative to the more veteran stakeholders. In addition, the public, and the media, often have an unfavorable opinion regarding the environmental effects of aquaculture in general, and net-cage finfish farming in particular (Mazur and Curtis, 2008).

Another factor that must be considered is the quality of coastal water. As human population continues its exponential increase, with a disproportional percentage living in the already crowded coastal regions, water quality in coastal waters is often poor. Activities that affect coastal water quality are not limited to those that occur at or near the water line, but actually all activities within watersheds (FAO, 1998). In protected bays and lagoons that are not strongly flushed these water quality problems are often exacerbated as nutrient and organic matter loadings exceed the ability of the ecosystem to dissipate these. In some cases, intensive mariculture may contribute to nutrient loading, water quality deterioration and benthic habitat destruction (Barraclough and Finger-Stich, 1996) and these may add to the negative image of the industry. In contrast, aquaculture of bivalves and seaweeds, also known as "extractive aquaculture" (Rawson *et al.*, 2002) generally removes nutrients from the marine system thereby improving water quality and potentially improving the public image of aquaculture. Since most marine organisms require good water quality to grow properly, it would be counter-productive to situate aquaculture facilities in waters with poor or variable water quality. Moreover, in many countries there are fairly stringent food-safety standards and these would preclude aquaculture in regions that are subject to water pollution.

In view of the considerations listed above, entrepreneurs in the mariculture sector began to look into the possibility of moving aquaculture systems away from the coast (e.g. National Research Council, 1992; Bridger, 2004). There are various advantages and disadvantages involved in moving aquaculture away from shore and this paper reviews some of them in the following sections. It is suitable to quote Neville Thompson's (1996) assessment of the four major factors that impact offshore aquaculture: "the market, costs of production, technology/expertise and funding availability". Although all of these are also applicable to coastal or sheltered aquaculture, the higher costs (and risks) associated with offshore ventures accentuate the importance of these aspects.

This review focuses on ecological/environmental aspects of "off-the-coast" and offshore tropical mariculture. Although there is an ongoing discussion revolving around the actual definition of, and distinction between, off-the-coast and offshore, this review will not dwell on these, but rather accept the formal definitions, as described in Table 1, where off-the-coast is the region of "coastal" waters that are near to shore but in semi-exposed conditions whereas offshore is further from shore in what we consider exposed and "open-ocean" conditions. The tropical region is defined as the area between the tropics of Cancer (23.5 N) and Capricorn (23.5 S). Although there are numerous examples of aquaculture in nearby subtropical regions that are warm and similar in many ways to the tropics, these will not be included in this review.

Definitions proposed by FAO for off-the-coast and offshore aquaculture from an environmental perspective and proposition of new boundaries

It is necessary from a policy/governance aspect to provide fish farmers, coastal managers, stakeholders and entrepreneurs with a clear idea of the distinction between coastal and non-coastal sites for aquaculture. However, with the criteria used for the three categories: coastal, off-the-coast and offshore, these are not satisfactory for defining what types of aquaculture can be practized at a given site. The categories preferred are "sheltered" and "exposed" or "open-sea" sites (see also Bridger, 2004) because despite the distance from shore, bottom depth or other physical features, the prevailing conditions at these sites (irrespective of their actual distance from shore) will determine whether aquaculture activities are practical/feasible. Where aquaculture is practized in bays (e.g. Sungo Bay in China), the waters may remain calm even as far out as 5 km or more from shore due to the prevailing winds and the orientation of the bay with respect to the "open sea". The definitions in this table state that coastal aquaculture is always accessible (and landing is always possible) when it is situated within 500 m from shore, but local conditions which vary considerably from place to place will determine whether or not this is true. The same argument applies to the proposal that off-the-coast aquaculture facilities situated 0.5–3 km from shore will be accessible >90 percent of the time; this will depend entirely on local conditions, since at some sites that are suitable for aquaculture, conditions are "exposed" within less that 0.5 km from shore, and as such, the sites will not always be accessible. The description of conditions and accessibility at offshore sites is more acceptable since these sites are basically oceanic in nature and fully "exposed". In terms of operation of aquaculture facilities, this is an important factor that needs to be included in the criteria, and the

TABLE 1
Proposed definitions (FAO) for coastal, off the coast and offshore aquaculture based on some environment and hydrographic characteristics. Present study will not involve directly "coastal aquaculture"

	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, 10 m <depth at low tide <50 m; 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, etc.	Some automated operations, e.g. feeding, monitoring	Remote operations, automated feeding, distance monitoring, system function

Terminology: Hs = significant wave height – approximately equal to the average of the highest one-third of the waves.
Source: Modified from Muir (2004).

authors would recommend placing the "distance from shore" in this rubric because it provides information on the difficulty/cost/energy involved in getting to the site from a practical aspect, and will play a major role in determining the economic feasibility of the activity. It is possible that one might want to consider a "fuzzy" approach (e.g. Cheng, Molenaar and Stein, 2009), incorporating both physical features at a given site and operational aspects, rather than use the clear distinctions (<500 m is coastal, whereas >500 m is off-the-coast) proposed in this table.

ADVANTAGES AND DISADVANTAGES OF MOVING AWAY FROM THE COAST

There are few differences among tropical and temperate aquaculture insofar as the rationales for moving away from shore. Offshore sites offer less competition with other stakeholders, more space, greater (seafloor) depths, a greater supply of dissolved oxygen and more rapid dilution of waste products released from the cages, with less of a perceived impact on the surrounding water and underlying sediments and healthier fish, i.e. a "greater" environmental holding capacity. In addition, because of their greater depth, offshore sites are less likely to affect ecologically-sensitive areas such as coral reefs, seagrass beds and mangrove forests. The disadvantage of offshore sites is their distance from hatcheries, maintenance and processing facilities and markets. The physical distance from shore to farm can be a major obstacle (logistically, financially and regarding their carbon or ecological footprint) on a daily basis since it is not feasible to house large teams of workers at sea for lengthy durations. The increased exposure (in comparison to coastal farms) of off-the-coast and offshore farms to severe storms considerably raises the investment costs required to protect the farm structures (e.g. moorings and nets) against the elements. Thus, economies of scale dictate that offshore farms must be larger-scale to cover these investment costs. These and other issues highlighting the pros and cons of moving offshore will be discussed in the following sections.

Advantages of offshore mariculture

The carrying capacity for dissolved nutrients and particulate organic matter depends on depth, current speed and acceptable environmental impact standards (Marine Aquaculture Task Force, 2007). Offshore cultivation of finfish provides several advantages over near-shore production.

Due to their size (assuming offshore cages will be larger than coastal cages) and location, offshore cages allow for more active swimming and provide cleaner water due to lower concentrations of shore-based pollutants and better clearance of wastes (Feng *et al.,* 2005; McVey, 2006). This results in healthier stocks with lower mortality. As a result, intensive application of antibiotics is rendered unnecessary. While coastal mariculture systems generally use antibiotics, most operational offshore systems studied did not apply antibiotics in their open-water facilities. This reduces the environmental impacts of antibiotic pollution and antibiotic-resistant pathogen development.

Depending on site placement and cage orientation, it is anticipated that offshore mariculture sites will experience higher flushing rates which will greatly reduce localized nutrification, related oxygen depression and algal blooms (Atkinson, Birk and Rosenthal, 2001; Cao *et al*., 2007). Effects on bottom sediments are dependent on the depth of the site and benthic flow regimes, but since offshore sites are likely to be deep, there is reduced concern about damaging sensitive, highly productive benthic ecosystems such as coral reefs and seagrass beds (Wu, 1995; Feng *et al.,* 2005; Beltran-Rodriguez, 2007).

The development of management schemes for offshore farms within ecosystem based management should incorporate studies of the ecological roles of biological assemblages, both wild and cultured. This information must be coupled with knowledge of nitrogen and phosphate fluxes from other anthropogenic sources such as land based agriculture, urban wastes and treatment plants and atmospheric deposition (Livingstone, Smith and Laughlin, 2000; Atkinson, Birk and Rosenthal, 2001; McVey, 2006). The removal rates of nitrogen as a result of biological activity have to be inferred to ensure prevention of local eutrophication.

Logistical advantages of offshore mariculture include reduced theft and vandalism, though this advantage is conferred by the relative disadvantage of reduced accessibility.

Growth of tropical offshore mariculture

In recent years there has been a gradual growth in offshore mariculture farms within tropical regions. Cage culture in general is undergoing a rapid growth and a shift from simple, semi-intensive cultivation towards more intensive systems (Halwart, Soto and Arthur, 2007), however this development often halts just short of the open ocean. The growth of offshore aquaculture appears to follow large-scale regional development trends, implying that industry growth is not primarily limited by site availability, but rather by availability of capital, technology and expertise.

The most successful aquaculture region to date has been Southeast Asia, mainly China (Feng *et al.,* 2005; Lovatelli *et al.*, 2008; Halwart, Soto and Arthur, 2007; Cao *et al.*, 2007). This trend is surprising in light of the low availability of capital and the challenging hydrography of the surrounding seas (mainly storms), which do not allow for the technology available elsewhere to be easily transferred and implemented there (Halwart, Soto and Arthur, 2007). Offshore farms have also been established in Hawaii (Marine Aquaculture Task Force, 2007), in the Caribbean (Bennetti *et al*., 2006, 2008) and in Oman (Al-Yahyai, 2008), and additional projects are planned for tropical South and Central America (Bennetti *et al*., 2008; Stemler, 2009) and Australia (Duckworth and Wolff, 2007). Other tropical regions such as African coasts, in which cage aquaculture is still in its infancy (Halwart and Moehl, 2004) have no offshore activity at all, except for European sponsored efforts in La Reunion, Mayotte and Mauritius (Dabbadie, 2009).

Table 2 summarizes current information on specific offshore mariculture projects by region. The majority of growth has been in systems which are distant from shore, but remain in relatively calm waters due to placement in broad, shallow zones of the coastal shelf that often benefit from sheltering bays or in/near peninsulas. This highlights the inconsistencies between the descriptive and functional definitions of offshore mariculture, since low-exposure offshore systems often combine the advantages, difficulties and requirements of both coastal and open-ocean systems in varying proportions. For example, locating a farm three kilometres from shore in a sheltered bay would result in high transportation costs and promote maximum automation even while obviating the need for heavy duty, storm-worthy submergible netcages.

Overall, the high cost and capital investment required for offshore mariculture incentivizes the cultivation of high-value species intended for consumption in the rich markets. Since carnivorous finfish fetch the highest prices within the current global market, most projects have focused on predator species such as cobia, snapper, amberjack, seabream, red drum, pacific threadfin and seabass. This departs from the majority of aquaculture in developing tropical nations, which is dominated by cultures of shellfish, shrimp and seaweed (for export) as well as milkfish and tilapia intended for regional/local consumption (Troell *et al.*, 2003).

New (previously uncultured) species are, or were recently, being developed for rearing in offshore facilities. These species include tuna (Benetti and Watchinson, 2000; Kent, 2003; Ottolenghi, 2008), amberjack (Chen *et al.,* 2008; Halwart, Soto and Arthur, 2007), Pacific threadfin (Kam, Leung and Ostrowski, 2003) and cobia (Liao *et al*., 2004; Bennetti *et al.,* 2006; Bennetti *et al.,* 2008; Nguyen *et al.,* 2009). Cobia culture has been successful from the onset due to the extremely rapid growth rates (up to 6 kg/individual/year) and high market price of this species (Bennetti, 2006; Liao *et al*., 2004). Tuna, though highly profitable, is cultivated as a value-added species only, since the life cycle of this species had not been closed and juvenile tuna stocks must be caught in the wild (Ottolenghi, 2008). A number of projects in Spain, Japan, Croatia and other nations are currently developing broodstock and hatching facilities for tuna (Kent, 2003). Until this technology is advanced, large-scale aquaculture of tuna remains unfeasible, and one of the alternatives – harvesting of wild tuna juveniles – would quickly deplete wild stocks.

Another group of fishes considered for offshore aquaculture is the flatfish. Summer flounder, *Paralichthys dentatus* is in great demand in the United States of America, and elsewhere. *P. dentatus* were the target of intense research as the coastal and fishery managers attempted to restock wild populations in Long Island Sound and to provide farm-reared fish to replace the wild caught fish when the flounder fishery plummeted (Bengton, 1999 and others). Summer flounder were also reared in offshore cages at GreatBay Aquafarms in Portsmouth, New Hampshire (USA).

Flatfish such as flounder, sole, turbot and halibut are also very lucrative in China, but their production was limited because these flatfish were cultivated only in indoor ponds or tanks. The introduction of the Chinese submersible cages now enables farmers to rear these flatfish in offshore farms (Chen *et al*., 2008) with excellent water quality and other advantageous growth conditions.

In addition, a number of projects have begun experimenting with offshore-compatible systems (bottom cages, bottom lines, etc.) for growing shrimp, scallop and mussels. These species may be especially useful as pollution-mitigating complimentary species for finfish in offshore polyculture. Conchs grown near-shore in Turks and Caicos as well as *Trochus* in several Pacific island nations could be expanded offshore. Bottom sponge culture is another branch of offshore mariculture which is being assessed for productive and economic viability (Duckworth and Wolff, 2007). Several finfish species have been suggested for future development, including the yellowfin amberjack (*Seriola quinqueradiata*) and mahi-mahi (*Coryphaena hippurus*) (Abellán and Basurco, 1999).

Corals on netcages and on netcage infrastructure

One of the recent findings that have come to light in warm-water net-cage aquaculture over the past decade is the recruitment of corals to farm structures. On the one hand, this is not surprising since corals release planktonic larvae into the water column and these settle onto available surfaces like many other “fouling” invertebrates. What is surprising is the fact that beyond their initial recruitment, Bongiorni *et al.* (2003) and others (e.g. Bosc, 2004) have found that corals growing adjacent to active fish farms are wildly successful in comparison to corals growing at nearby reference sites. In addition to the corals, there are numerous sponges and a myriad of invertebrates that develop on farm infrastructure in warm waters, as well as reef fishes that associate with the invertebrate community (D. Angel, personal observation). Although it would involve some research and development, these findings indicate that tropical offshore fish farms could serve as a basis for cultivation of corals and reef organisms for the marine aquarium industry and for coral reef restoration efforts.

Highest potential for growth

Due to the fact that offshore aquaculture involves large capital investment, considerable technological know-how and a strong export (or local profit) potential, this industry is most suitable to the tropical regions in Southeast Asia, Brazil, India and developed Central American countries (Belize, Mexico, Costa Rica, etc.). In Africa, the Caribbean and the Pacific Islands (Oceania) the industry faces challenges related to inexistent infrastructure and unavailable capital. In an attempt to make aquaculture more profitable, high-end fish may be chosen but the industry will fail if the nearest markets are too far away to be economically competitive (high transport costs). In many countries, the local economy does not have the necessary capital to get started, and in such cases, foreign companies establish the industry (see examples below), bringing with them various questions related to equity and environmental integrity.

The highest potential culture species in the tropics appears to be cobia, and indeed, the countries mentioned above have shown interest in or taken first steps toward its rearing and culture. India is in the process of investigating the option of cobia offshore farming (20–30 m depth) using Norwegian (polar circle) cages near Tharuvikulam in Tuticorin (Kerala). This is expected to give some of the much-needed boost to the country’s rising seafood demand and export market. Central and South America are currently taking first steps toward cobia farming. In Ecuador, the United States of America based “Ocean Farm”, company that developed the “Aquapod” technology, plans to start raising cobia using HDPE cages. The Aqualider and TWB companies in Brazil already rear cobia, and in Panama Pristine Ocean, Farallon and Ocean Blue Sea Farms are all planning offshore cultivation of cobia, snapper and other species.

Mariculture of cobia and other marine species has been evaluated and reviewed for Namibia (Iitembu, 2005) in a first mainland African endeavor in this direction, but the industry has not yet developed there.

Although it lags behind cobia, another lucrative warm water fish with great potential for offshore growout is the tuna. Mexican farms (mainly in Baja California), driven by considerable U.S. investment currently fatten more than 5 000 tonnes annually of bigeye, bluefin and yellowfin tuna (Morales and Morales, 2005; Halwart, Soto and Arthur, 2007). In Costa Rica a tuna farm was planned on the mouth of the Golfo Dulce, two kilometres off the coast (Rojas and Wadsworth, 2007), however, these plans faced strong opposition from local surfers and environmental groups and the future of this venture is unclear.

In Martinique, the endemic (Gulf of Mexico) red drum is reared in net cages in a local bay and although conditions there are considered “sheltered”, this farm successfully withstood a hurricane that devastated large parts of the Caribbean, suggesting the technology can probably be taken offshore, as is. Similar cage-culture activities are under way in the Indian Ocean islands, La Reunion and Mayotte.

Challenges facing offshore mariculture

One of the challenges facing offshore mariculture is the uncertainty we have regarding environmental and ecosystem effects of the industry, mainly because currently there are few offshore, commercial-scale operations and very little information on their interactions with the surrounding system. The distance from shore and greater water-column depths of offshore facilities should reduce ecological impacts, as well as impacts related to escapes and disease, based on our understanding and experience with coastal aquaculture. However, the distance from shore also means increased exposure to storms and to large predators, hence, potential damage to the farm structures and the farmed stock. The use of offshore waters also raises many legal questions such as the rights of individuals or nations to "lease the ocean" (Middleton, 2004; Rimmer and Ponia, 2007).

Environmental effects of offshore systems

Considerable aquaculture impact research has been carried out at warm water subtropical sites that are similar in many ways to tropical sites (e.g. Angel *et al.*, 1995; Pitta *et al.*, 1999; Karakassis *et al.*, 1999; Machias *et al.*, 2006; Apostolaki *et al.*, 2007; and others). These studies suggest that intensive aquaculture activity will most likely affect the benthos, though the degree of the impact will be a function of the prevailing site-specific conditions (e.g. Atkinson, Birk and Rosenthal, 2001; Kalantzi and Karakassis, 2006; Mantzavrakos *et al.*, 2007), farm husbandry and management.

Whereas "offshore" or "open-water" sites are thought to reduce the benthic impact of net-cage fish farms by virtue of the greater seafloor depth and exposed conditions, this is a contentious topic at some tropical aquaculture sites. It has been reported, for example, that sediments under offshore Pacific threadfin farms in Hawaii showed negligible benthic impacts (Helsley, 2006). Recent findings at the same sites suggest this is not necessarily the case. Infaunal communities sampled near the fish farm have shown a clear temporal shift in species richness and composition in comparison to a reference site (Lee, Bailey-Brock and McGurr, 2006), and have only undergone partial recovery during a 6-month fallowing period (Lin and Bailey-Brock, 2008).

At the Snapperfarm facility near Puerto Rico, the effects of cobia (*Rachycentron canadum*) and snapper (*Lutjanus analis*) reared in offshore net cages on the environment were monitored. The monitoring included measurements of dissolved nitrogen and phosphorus, phytoplankton biomass, epiphyte growth potential, particulate organic matter flux, organic content of the sediments, and benthic microalgal biomass. During the demonstration phase of the project (50 tonnes produced/year) Alston *et al.* (2005) examined the environmental effects and concluded that these were trivial. This led Bennetti *et al.* (2006) to report that "in no case were significant differences found as a function of distance from the cages or relative to upstream-downstream direction". Beltrán-Rodríguez (2007) examined changes in sediment biogeochemistry one year after cages were more heavily stocked. Her results showed a significant nutrient and organic matter enrichment in the sediments under the farm, as compared to reference sites. Morales-Nuñez (2005) carried out a parallel study of the sediment fauna and reported an increase in Tanaidaceae (Crustacea) abundances and a decrease in macrofauna diversity at the end of the year-long study. These results suggest that the farms that were studied are not what we would consider truly "offshore" farms, or that the farm husbandry may not have been very good. Hincapié-Cárdenas (2007) examined the dynamics of biofouling communities on the Snapperfarm cages in an attempt to assess whether offshore farms which are potentially more isolated from large concentration of planktonic larvae, for example may be less susceptible to fouling than near-shore farms. Results showed that there were no significant differences between the fouling communities on cobia versus snapper cages. Unfortunately, the study did not include a comparison between the fouling on these offshore cages versus onshore or coastal farms. It is noteworthy that despite their small-scale, several environmental studies were carried out and published with regard to Caribbean and Hawaiian offshore farms. Unfortunately, there are very few publications on environmental assessments of the much larger Chinese off-the-coast and offshore operations.

The organic enrichment of the seafloor under aquaculture systems is generally viewed in a negative light due to considerable experience in shallow coastal waters, where hypoxic/anoxic sediments have generated virtual "dead zones" below net pens. It is possible, however that in deeper waters in tropical, oligotrophic regions the detritus from aquaculture operations may serve as an attractant to benthic detritivores, thereby altering the composition of local communities and benthic food webs, which could have wider, possibly "positive" implications on the ecosystem, as described by Machias *et al.* (2006).

Most studies of the water column around coastal aquaculture in subtropical regions have found either no effects or only slight increase in such water quality indicators as nutrients, turbidity and chlorophyll-a (Wu *et al.*, 1994; Wu, 1995; Helsley, 2006; Pitta *et al.*, 2006 and 2009). There have also been a few observations of substantially reduced water quality conditions around farms that were improperly sited (e.g. Aure and Stigebrandt, 1990; Wu *et al.*, 1994) since these suffered from inadequate flushing of metabolic wastes. It is anticipated that tropical offshore aquaculture will have similar interactions with the surrounding waters and one of the main criteria that should be considered when selecting farm sites, configurations (layout of cages and infrastructure) and orientations (with respect to currents) is the ambient hydrodynamic regime. Although it is assumed that the physical environment becomes more energetic with distance from shore, this is not necessarily so and the hydrodynamic regime should be assessed during the site selection process. It has been suggested that tropical offshore areas are more oligotrophic and as such, can receive greater loadings of nutrients (in comparison to mesotrophic areas, for example) before developing water quality problems. The premise here is that the dogma "the solution to pollution is dilution" actually works, yet it is not clear that it actually does.

Although we tend to think of macrophyte aquaculture as extractive and therefore ecologically "beneficial" or benign, there is evidence of a variety of impacts of tropical open-water seaweed farms on the surrounding environment. Seaweed aquaculture may impact seagrass systems (Eklöf, Henriksson and Kautsky, 2006), macrofauna (Eklöf *et al.*, 2005), meiofauna (Ólaffson, Johnstone and Ndaro, 1995) and even fish communities (Eklöf *et al.*, 2006). These impacts include the dispersal of the cultivated seaweeds to seagrass meadows where they may act as a source of shading (as epiphytes on the seagrasses or seaweed detritus) and organic loading which may lead to habitat alteration, hypoxia and in some cases destruction. The macrophytes may also serve as an added source of nutrients to herbivorous fish (e.g. siganiids) which normally inhabit seagrass beds, thereby enhancing fish populations and as such, the impact may even be positive from the perspective of fishers.

Unlike fed aquaculture which involves addition of feed to net cages, extractive aquaculture relies on natural plankton for bivalve growth, i.e. it is "extractive" (cite). In eutrophic waters, the removal of phytoplankton from the environment is generally considered a positive outcome of the industry, however, it is really a question of scale. If the size of bivalve farms is very large, they will have a significant impact on local phytoplankton communities (Tenore, Corral and Gonzales, 1985) and the benthic organic loading due to deposition of faeces and pseudofaeces may be considerable (Stenton-Dozey, Jackson and Busby, 1999; Chamberlain *et al.*, 2001). If bivalve aquaculture is situated in tropical offshore waters, these waters will need to be assessed with respect to what large scale grazing of phytoplankton may do to the local populations of planktonic and benthic herbivores.

Environmental impacts due to disease and escapes

Disease is one of the major concerns of all farmers, including marine farmers, as it may lead to rapid loss of the cultivated stock. In many cases, pathogens originate from wild fish or invertebrate populations (e.g. Diamant and Paperna, 1995) but may reach epidemic proportions in intensively cultivated net pens, as in the case of sea-lice and salmon (Goldburg and Naylor, 2004; Naylor and Burke, 2005). This threat is also a source of concern to environmentalists since disease may rapidly spread from farmed organisms to wild stocks (e.g. McVicar, 1997) with widespread community-wide impacts. Pathogens abound in all environments, but due to the greater natural biodiversity in the tropics, there is also a larger diversity of disease agents (Avise, Hubbell and Ayala, 2008). In addition, the rate of infection is magnified due to the naturally high ambient temperatures which affect metabolic rates of hosts and pathogens alike, and their activity levels. One of the most important water-quality factors that affect most of the cultivated marine animals is dissolved oxygen. As temperature and salinity levels increase (higher temperatures often lead to higher salinities), the concentration of dissolved oxygen in seawater decreases so that in perpetually or generally warm water regions (tropics), animals are constantly dealing with oxic stress and are therefore, more susceptible to disease. In addition to oxic stress, a problem that has emerged in the cultivation of (the tropical) cobia in Taiwan Province of China is sensitivity to seawater temperature. It appears that this fish becomes stressed and more susceptible to disease when temperatures drop below its optimal growth temperature (Liao *et al.*, 2004), as observed when comparing the survival and growth rates of cobia reared in Penghu Islet (northern part of China) as compared to Shiao-Liu-Chio, Pingtung (southern part of China).

If it is assumed that the frequency of diseased fish is higher in captive (farm) populations (Costello, 2006), then one mechanism for broadcasting disease is a massive release of (escaped) fish, e.g. following net cage damage. There are, as yet, no documented cases of disease outbreaks as a direct result of these escapes.

Many escapes have been documented in the marine environment. Net pens in the Dominican Republic and Mexico sustained considerable damage following hurricanes and many of the stocked fish (estimated 60 000 cobia) escaped in 2007 (Benetti *et al.*, 2008). Typhoons in Taiwan, Province of China caused similar effects releasing large numbers of farmed fish thereby leading to a major decline in production in 2001 and 2002 (Liao *et al.*, 2004). Escapes have also resulted from human error during cage maintenance and harvesting activities, collision of ships with net-cage farms, sharks or other predators tearing net-cages (Food and Water Watch, 2009b) and vandalism (D. Angel, personal communication, 1997).

The escape of farmed fish may have detrimental effects on wild fish populations through competition and interbreeding (Naylor and Burke, 2005). This aspect of environmental interaction has been studied in depth in Canadian aquaculture. One of the advantages of offshore farms that are situated far from shore is the potential reduction in vandalism, though there is a need to monitor and guard these offshore facilities. In addition, escaped fish may have a lower impact on the environment that they are introduced into, by virtue of their distance from shore and the pelagic environment that may be the "wrong" habitat for the fish. Thus, despite numerous escape events of large numbers of fish, there are few examples of successful fish introductions in marine environments (Baltz, 1991; Billington and Herbert, 1991). This statement regarding low levels of impact should be accompanied by the caveat that our level of knowledge regarding fish communities and their resilience is rather limited in many parts of the ocean. Application of best practices and technology should limit escape events to a minimum. This may partially be achieved by good site selection, as in the case of aquaculture in Brazil, Belize and Panama which are known for their low frequency of hurricanes and strong storms (Benetti, 2008). In addition, good husbandry, including routine disposal of dead fish should reduce the attraction of predators, such as sharks, thereby reducing the risk of escapes even further. Stronger nets, monitoring systems e.g. motion-detection sensors, and proper planning of farming operations are all readily available solutions to reduce escapes. In this aspect (prevention of escapes), there is no distinguishing feature to differentiate tropical from temperate aquaculture, though the predators are inherently different (sharks in the tropics versus sea lions in the temperate zone). State of the art information regarding escapes and developments to reduce this problem may be found at the Web site of the European Union project (www.preventescape.eu). It is noteworthy that there are cultural differences with regard to the outlook on escapes, i.e. whether they are detrimental or beneficial. In many western countries, e.g. Canada, United States of America, Norway, escapes (especially salmon) are considered a tremendous detriment to natural stocks as they may dilute the natural gene pool and spread disease. In Asia, there is a lot less concern about the environmental consequences of escapes and in some cases, the escaped fish are considered a good means for restocking natural fisheries.

Despite their distance from shore, offshore farms tend to serve as efficient fish attracting "devices" (FAD). The mechanism underlying this process is not clear, since many coastal species are not known to migrate over great distances, but the facts speak for themselves. Many tropical and subtropical farms are surrounded by large populations of wild (and in some cases feral) fish (e.g. Boyra *et al.*, 2004; Dempster *et al.*, 2002, 2004) which fill different ecological roles. Some of the fish (planktivores) feed on phytoplankton and zooplankton that tend to concentrate around the cages, while others (detritivores) act as "sinks" for lost feed and feces that are released from the cages. Numerous predatory fish are attracted to the cages by the presence of the planktivores and detritivores that congregate around the FADs and others, e.g. sharks and seals are attracted by the caged fish stocks themselves (Tuya *et al.*, 2006). The attraction of large predators to the cages endangers the caged stocks (which could lead to additional escapes) and the farm employees that maintain the cages by diving.

Shark attacks on cages in the Bahamas and in Puerto-Rico have damaged nets. As a consequence of subsequent escapes, the entire economic viability of some farms was compromised (Bennetti *et al*., 2008). With respect to causes of damage to cages, shark attacks are prevalent in the Caribbean (Bennetti *et al*., 2008) and in Hawaii (Food and Water Watch, 2009a, b), whereas storm damage was the main problem for cages in such regions as China, Mexico and the Dominican Republic.

In addition to the attraction of pelagic fish to fish farms, benthic enrichment under cage sites may serve as a FAD for benthic detritivores, altering local biogeography and benthic food webs. These changes may have an impact on community composition and nutrient regime shifts may follow.

Potential ecosystem effects

One of the main motivations of marine aquaculture is to supply the marine products (both in terms of rare species and volume) that conventional fisheries can no longer provide. On the ecosystem level, this may ultimately mean reduced pressure on natural fisheries, provided aquaculture can find alternatives to fishmeal and fish oils. A reduction in fishing pressures in areas where aquaculture serves as an alternative supplier should enable the recovery of many benthic and pelagic communities and could have ecosystem-wide ramifications. This is a topic that would greatly benefit from the involvement of policy-makers and politicians.

The transition from coastal aquaculture to offshore practices may have less of an effect on the local-scale, as we increase the dispersal of fish farm effluents at such exposed sites, but greater impact on an ecosystem level. Machias *et al.* (2006) and others have found evidence of regional and ecosystem level effects, e.g. increased fishery landings as a consequence of increased aquaculture production. An increase in dispersal of nutrients from large offshore farms could create a large trophic ripple effect, as anticipated in the models developed in the MARICULT project (Olsen, 2002), though it is not clear whether these would generate desirable or undesirable changes.

In some commercial species, it is difficult or prohibitively expensive to complete the life cycle in captivity and the growout process relies on collection of fingerlings from wild stocks. This currently happens, for example, with grey mullets in Egypt and places heavy pressure on wild stocks. The same occurs with grouper farming in SE Asia and as it is done in an unregulated manner, wild stocks may be driven to extinction. In some countries in Central and South America, this issue has been addressed and offshore farms are required to construct hatcheries before cage systems are deployed to prevent wild fry fishing. Large efforts are being made to solve this problem for tuna aquaculture in Australia, United States of America, Japan and in the European Union.

There are also problems related to the feed used in fish farms. In many tropical countries carnivorous fish are fed “trash” fish (a term used to describe fish that are not usually eaten or sought after as sport fish or otherwise by fishers). This practice is extremely wasteful, and has a very high feed conversion ratio (FCR). This practice also places greater pressure on a variety of wild species, that are not normally targeted as commercial fish and raises questions with regard to by-catch and whether there should be more or less incentive to use the products of fishery by-catch. Thus, there is concern that by virtue of expansion of the cage aquaculture industry into offshore areas the need for fish feed will have widespread impacts on more wild stocks than are currently targeted and exploited by the fish-feed industry.

Carbon footprint

While offshore farming may mitigate effects on the local ecosystem by moving nutrient, pathogen and chemical sources away from fragile coastal or estuarine waters, the additional energy required for access and transportation to remote farms should be factored in before a net ecological footprint is calculated. Increased fuel costs and carbon emissions from employee access, maintenance, feed delivery, stocking and harvesting must be accounted for, though some of these are certainly offset by energy savings in water oxygenation and filtration when compared with land-based farms.

One of the major factors affecting the carbon footprint of the aquaculture industry is the proximity of feed stocks and the distance to market, the latter being especially important since high-value species (e.g. bluefin tuna) are generally delivered by air when exported. Tropical mariculture projects designed to meet import demand of wealthy countries would have a dramatically larger carbon footprint when compared with projects designed to supply local markets. One way to reduce the carbon footprint of exported high-end species is by establishing and developing local markets as was done with cobia in Taiwan, Province of China (Liao *et al.*, 2004). The market for live food fish is substantial and is increasing, not only in Asia but throughout the world, though records indicate that roughly 40 percent of the trade goes through Hong Kong SAR (Nguyen *et al.*, 2009). In Hawaii, the Kona Blue Water farm rears Hawaiian yellowtail, *Seriola rivoliana*, in open-water cages and targets this fish toward local Hawaiian, and the tourist, market under the brand name “Kona Kampachi”.

Another aspect of the carbon footprint that should be considered is the fish that are used in preparing the farmed fish feed. Feeding with “trash fish” from local fisheries would reduce transportation and processing related emissions when compared with the use of fish meal or fish oil which are produced from species which are fished in the high latitudes, e.g. anchovy and herring. But this would contribute to a greater problem of nutrification, since trash fish are a less efficient food source (lower FCR) (Naylor *et al.*, 2000). In addition, targeted trash fish extraction (as practiced in parts of Southeast Asia, mostly by trawl fisheries) impacts local food webs by removing certain size classes and species (Hall, Alverson and Metuzals, 2000), as well as, having severe detrimental effects on benthic habitats (Watling and Norse, 1998).

Policy-makers

In many countries (e.g. Israel, Cyprus, Turkey, United States of America) policy-makers have reacted to the demands of lobbyists and veteran (non-aquaculture) stakeholders with respect to the coastal zone and have limited the development of aquaculture to non-coastal or off-the-coast sites. This is a source of optimism for offshore aquaculture development, but there are also many obstacles blocking the way, mainly related to governance.

Governance

Addressing the effects of aquaculture on the marine environment requires changes to the broader framework of laws, institutions, and policies that dictate how aquaculture is sited, permitted, and operated in marine waters. This is particularly true if aquaculture moves increasingly offshore into marine waters under national jurisdiction. Two key failings of the current legal regime for marine aquaculture in many countries are the lack of clear national leadership and the lack of standards to protect the marine environment. Numerous federal agencies have responsibility for aspects of aquaculture regulation, but currently no agency is charged to coordinate the overall process. This creates a confusing and cumbersome process for those seeking permits for aquaculture and results in a lack of accountability among the agencies for marine aquaculture activities and its impacts on the marine environment.

A growing need therefore, emerges to establish a marine aquaculture programme that is precautionary, science based, socially and economically compatible with affected coastal communities, transparent in its decision-making, and provides ample opportunity for public input.

Potential socioeconomic effects

There are various socioeconomic ramifications involved in the development of offshore aquaculture in the tropics, as compared to the existent coastal aquaculture industry. Ownership and operation of offshore farms by individual farmers is a substantial economic hurdle due to the large initial investment required. These investments include extensive and massive mooring arrays, seagoing vessels for maintenance and feeding, etc., that are not required in coastal operations. Even if an entrepreneur overcomes the initial capital investment obstacle, the high risks associated with offshore mariculture further discourages smaller operators from entering the industry. Deployment and management of a farm at an offshore setting requires more highly-skilled workers than are needed in coastal aquaculture, since there is a large degree of seamanship and SCUBA divings involved in addition to routine aquaculture husbandry and thus jobs tend to be higher paid. On the positive side, it is highly likely that the success of offshore aquaculture will mark a great expansion in production volume which will generate demand for all of the peripheral industries such as marketing, feed and seed production, processing and other downstream added value industries, and thus, generation of many more jobs. In areas which have high unemployment, this has the potential to boost the economy and help develop ailing communities.

Another possible outcome of moving farms offshore is the increased reliance on automation rather than manpower. This is due to the need for sophisticated systems to address difficult and dangerous weather and sea states and in that case, the number of available jobs at the farms themselves might actually be more limited. Liao (2000) describes the socioeconomic problems that farmers in Taiwan, Province of China face as "high production costs, marketing factors, user conflicts, and lack of infrastructures". Whereas marketing problems and user conflicts may actually decrease, production costs and lack of infrastructure tend to increase when moving offshore, as described at length in the technical reviews (this volume). Moving farms offshore requires farmers to increase farm volume and focus on more profitable species in order to balance the high production costs with high profit. For Southeast Asia, this mandates growing larger, more predatory species fit for the Japanese Sashimi market, for example (Liao, 2000). Since feed is still the major cost component in farm expenses, the choice is between cheaper, low FCR trash fish, which are also more detrimental to the environment, and the more expensive pelleted feed.

Additional socioeconomic issues that need to be taken into consideration include: a) Considerably greater technical skills and maritime expertize: offshore farms, especially those in exposed sites, involve skilled seamanship, SCUBA diving in difficult conditions and greater "farming-in-extreme-conditions" skills as compared to mariculture near the coast; b) user conflicts, including competition with fishers, shipping lanes, offshore mining, communication cables, underwater gas lines, etc.; c) socio-economic sustainability. Because offshore farms are more of a debate than a reality in many countries, this aspect of offshore aquaculture is really only emerging at the present time, but it is an area that is essential to the industry and needs to be explored with regard to the feasibility of offshore aquaculture.

NGO response and organic label debate

Various NGOs are opposed to offshore aquaculture, though their motivations are often not very clear. One of the patterns that recur in some of the NGO statements is a blanket statement regarding the negative effects of aquaculture on the environment without actually addressing the differences between coastal and offshore aquaculture. Food and Water Watch (FWW) is opposed to sea-based aquaculture and is concerned that offshore producers will seek an organic label ("green" seafood) based on the premise that offshore enterprises may cause less environmental damage. The National Coalition for Marine Conservation is another NGO that is opposed to offshore aquaculture yet their document does not really address the conditions and issues in offshore waters. Naylor (2006) has covered some of the prime issues that the aquaculture sector must address in developing an environmentally acceptable and sustainable industry. One of the strong claims of NGOs is related to the aesthetic damage caused by coastal fish farms (also known as NIMBYism = Not-In-My-Back-Yard), but this is generally associated with wealthy land and home owners. Because many of the communities in tropical (developing) areas are poor, it is anticipated that offshore aquaculture will not address many NGO concerns related to aesthetics. Despite the many advantages conferred by offshore aquaculture, the increased carbon emissions related to the carbon footprint (described above) may offset some of the ecological benefits.

Mitigating factors for offshore aquaculture

Integrated aquaculture potential

Whereas the norm in mariculture is monoculture, the cultivation of one species, farms that rear fish, shellfish and seaweeds in bays and lagoons have operated in the Pacific and Indian oceans for many years (Neori *et al.*, 2004), especially in mainland China. Because of the logistical difficulties involved in offshore systems, it would appear that the optimal type of integrated culture is polyculture of different, yet compatible species in cages. Simultaneous, sequential or temporal integration are also possible depending on cultured species and the desired outcome.

Both integrated and offshore mariculture seek to solve nutrification problems caused by conventional coastal mariculture, but they do so via two different mechanisms. Whereas integrated systems diversify production to induce biofiltration, offshore farms shift the nutrient load to environments with a higher carrying capacity and greater flushing rates. Troell (2009) reviewed the potential of farm diversification and integration of different species of organisms in the tropics in order to benefit from the synergy. Out of nearly 100 studies of integrated systems that he reviewed, 16 percent dealt with open water integration; most of these included seaweeds. The main objective of integrating fish or shrimps with seaweeds or mussels is for the latter to act as a biofilter and mitigate eutrophication effects of the farms. Although such systems make ecological "sense", a proper balance between the cultured components in such an operation is a pre-requisite for successful, efficient and profitable production. Most studies were performed on a small, experimental scale but did not include an economic analysis, to calculate feasibility and profitability. The combination of moving farms offshore and integration of systems requires that several demands are met: a) there must be sufficient dissolved and particulate matter in the water column to support the lower trophic levels; b) the seaweeds or mussels surrounding a fish farm must be adjusted to higher energy fluxes that exist in offshore surroundings; c) if submersible systems are used, changes in light penetration and ambient pressure must not affect growth and survival of the integrated organisms.

Oyster and seaweed co-cultures are practiced in many off-the-coast operations, mainly in China, and are the most common type of integrated systems in open waters. Nevertheless, these are mostly practiced in protected bays and shallow coastal waters. Several examples of integrated open farms already exist in the tropics: oyster-seaweed systems in China, an experimental system for *Trochus* and giant clam restocking in the Solomon Islands and shrimp and seaweed systems in the Philippines (Lombardi *et al.*, 2006).

Recent studies have shown that corals growing adjacent to finfish net cages have higher growth rates than corals growing at pristine reference sites and on coral reefs (Bongiorni *et al.*, 2003; Bosc, 2004; Shafir, Rijn and Rinkevich, 2006). These findings may enable the integrated cultivation of corals with aquaculture for the marine aquarium trade, remediation and restocking of natural reefs or alleviation of diving pressure on natural reefs.

Troell (2009) notes that the key difference in the approach toward integrated systems in tropical versus temperate zones stems from lack of environmental awareness to waste mitigation in the tropics. This lack of awareness may prove a decisive factor in the overall deployment of offshore systems in the tropics, as high cost of offshore farms often obscures the benefits of mitigations.

Whereas offshore aquaculture may offer solutions to some of the problems that characterize coastal farms, other issues, such as biofouling, predators and stress-related disease are often just as much a problem in offshore farms. Oronti and Thiago (2009) propose a low cost solution to these problems by mimicking natural marine processes. They suggest that an artificial ecosystem may be created within the cages that would include the various trophic levels needed to maintain a clean and healthy growth environment. This would include: herbivorous species, such as rabbitfish, that would keep algal fouling of the nets to a minimum, detritivores, e.g. crustaceans or sea cucumbers to consume uneaten fish feed and faeces, scavengers to consume dead fish and even cleaner fish to improve overall fish health. This concept is somewhat utopian since it assumes that the organisms representing the various trophic levels will co-exist harmoniously, but it is worthwhile examining.

Synopsis of ongoing offshore aquaculture activities in tropical regions

The majority of tropical offshore aquaculture activity is concentrated in two regions, the Far East and the Caribbean/USA-Hawaii. Off-the-coast and offshore aquaculture in the Far East is dominated by China and Taiwan, Province of China which have already achieved commercial scale activities. Lucrative predatory fish prices from regional markets in Hong Kong Special Administrative Region and Japan and limited space in overcrowded bays and coastal lagoons are driving aquaculture companies offshore and are attracting poorer neighboring countries, such as Viet Nam into the practice. The paucity of offshore systems in countries with considerable experience in mariculture such as the Philippines, Malaysia, Indonesia or Thailand is surprising, and can probably be explained by a lack of private investment and governmental support. In comparison, there is obvious government involvement in offshore farms in Taiwan, Province of China (Liao *et al.*, 2004) and in China (Feng *et al.*, 2005).

Most Chinese mariculture operates in shallow seas, mud flats and protected bays. The main production types of coastal and off the coast aquaculture are floating and semi-floating raft culture, net cage culture, seabed seeding, vertical (hanging) culture and ponds in tidal areas (Cao *et al.*, 2007). High organic nutrient loading may lead to environmental degradation, especially when trash fish are used (Wu, 1995) because of the high FCR of this practice as Chinese coastal waters are shallow.

The development of deep-water offshore cages in China was initiated in the late 1990s. In 1998 the first offshore cages (four cages, 40 and 50 m in perimeter) were introduced into Hainan Province from Norway. Another 32 offshore cages were introduced and installed in coastal provinces including Shandong, Zhejiang, Guangdong and Fujian since 2000. From then on, developing and extending offshore cages has been confirmed as a priority of marine fish farming by the Chinese government and relevant authorities (Lovatelli *et al.*, 2008). Pompano is the main cultured species in the southern provinces (Cremer *et al.*, 2006).

Seed for the high-end offshore species in China and Taiwan, Province of China is almost exclusively hatchery reared and feed is mostly pellets, with some trash fish still used. Despite this, Chen *et al.* (2007) argue that the prospects of widespread development of offshore systems in Asia is unlikely and is hampered by the lack of investment capital and by the hydrography of the surrounding shallow seas, making adoption of technology available elsewhere difficult.

The second region where substantial offshore activities are recorded is Hawaii (USA) and the Caribbean (mainly Puerto Rico and Bahamas), where the United States of America is the major force driving the development of experimental systems. A growing interest is also emerging among aquaculture companies based in other central America countries, including Panama, Belize, Mexico, Costa Rica and others. The emphasis in the Caribbean is still on development of technology and the shift to commercial scale production is expected to take place in the coming decade.

In both the Far East and the Caribbean, the trend is generally toward rearing of pelagic fish, with cobia and snapper the primary aquaculture species.

Isolated tropical ventures also exist in the French influenced islands of Martinique and Mauritius, Mayotte and La Reunion in the Western Indian Ocean. There is also an Omani farm growing seabream and seabass using the "Mediterranean model", some Australian offshore Barramundi farms and an experimental offshore sponge ranch.

Many of the countries in the tropical region have plans to develop or are in early stages of development of their aquaculture industry. Because this is a highly dynamic industry with large potential, yet many risks, aquaculture ventures rapidly rise and fall and only some (usually the successful) companies in selected countries are accompanied by monitoring or research that eventually yields reports and publications. A few of these developments are described below.

In Papua New Guinea, a barramundi sea cage farm was established off-the-coast of the Madang Province, as a community program. It is in a somewhat protected area and reached 100 tonnes at its peak. The farm sustained storm damage and is scheduled to be reopened, following repairs during 2010. Fry is locally produced and feed is locally gillnetted trash fish (Middleton, 2004).

There are only three barramundi sea cage farms in Australia and two of these are located in high energy environments. The Northern Territory farm is subject to tidal amplitudes, up to 8 m, while the Queensland farm is situated in an estuary with lower tides (up to 3.5 m) but with high velocity currents during strong tides. The strong currents that the farms are exposed to have resulted in both farms moving away from traditional mesh cages to more rigid designs utilizing steel or plastic mesh cages. Barramundi are fed pellet diets, and there has been much research done on developing cost-effective diets, including high-energy diets. Although automated feeding systems have been used on the large-scale sea cage farms, most barramundi farmers feed manually. Food conversion ratios for cage culture of barramundi vary widely, ranging from 1.3:1 to 2.0:1 during the warmer months, and increasing during winter.

Table 2 provides a non-comprehensive overview of information on current off-the-coast and offshore aquaculture in the tropical regions (between the Tropics of Cancer – 23.5 N and Capricorn – 23.5 S).

STATUS OF OFFSHORE AQUACULTURE IN TROPICAL REGIONS

The initial challenge in moving aquaculture offshore was technological, as traditional methods were suitable for sheltered, low-energy environments. Despite some storm damage the offshore systems employed have thus far passed the physical tests the ocean has put them through, and must now face other feasibility issues. In Southeast Asia, governmental subsidy and entrepreneurship as well as spatial constraints have propelled offshore aquaculture to full commercial scale. China and Taiwan, Province of China have thousands of years of experience in aquaculture, therefore skilled labor is never hard to find. Moreover, producers have considerable biological and operational know-how regarding hatcheries, nurseries, feed and growout technology. Consumers in these and neighboring countries (mostly Japan and Republic of Korea) constitute an almost insatiable market for mariculture products. Furthermore, new capital is readily available and governments are eager to invest or subsidize the mariculture sector. There are national aquaculture plans in China and in Taiwan, Province of China to expand the sector and this is bound to aid in further development of offshore aquaculture. This favourable "climate" is such that in these countries user conflicts or environmental criticism is not likely to interfere with offshore development.

Constraints in Southeast Asia are mostly hydrographic and some researchers (Chen *et al.*, 2007) claim they will limit production considerably. Viet Nam is a new player in the offshore aquaculture industry with credentials in the freshwater and inshore marine sector. Viet Nam also fosters a government-backed offshore plan and is expected to become a major contributor to mariculture yields in the near future. Other Southeast Asian countries with aquaculture experience are expected to venture offshore in the future as demands and prices increase and provided the risks are reduced, but they are currently not developing in this direction.

The Caribbean region is a different story. Here, technology is scrutinized in detail before licenses are granted, governments subsidize and companies invest. The climate is still one of pioneering and trial and error and thus great plans are drawn but have so far remained mostly on paper.

This is especially true for cobia, hailed as the main culture species of offshore systems. In 2005, 80 percent of the 32 000 tonnes grown worldwide were produced in China and the rest in Taiwan, Province of China (Morales and Morales, 2005). Bennetti *et al.* (2007) predicted exponential growth rates for Caribbean cobia: from 50 tonnes to 1 000–3 000 tonnes in 2010 and 5 000–10 000 tonnes in 2012 for the offshore farm industry. These predictions were not met. This growth estimate was based on the assumption that foreign investment would enable rapid development, but that did not happen. Whether or not this growth will eventually occur remains hard to predict. User conflicts, environmental criticism and sluggish governmental involvement and backing still hamper individual efforts of companies. Nevertheless, the way forward has been plotted and many countries in Latin America appear to be potential growers, with hatcheries and onshore facilities already installed in most of them. The Hawaiian (USA) experience, despite its relative success, is also still more of a feasibility study than a successful business at commercial scale.

Australia is another country with a long tropical coastline. The main cultured species is barramundi and the few offshore farms are still isolated cases, rather than a large scale-up. Here as well it seems that legal and environmental constraints will delay production. Other ventures, such as those in Oman or the Islands of Reunion

TABLE 2

A regional synopsis of off the coast and offshore aquaculture in the tropical regions. Column headings include: country (or region)[1], major species and production levels[2], site exposure level (despite distance from shore and water depth, the degree of exposure will determine the level of investment required to withstand rough seas)[3], currents and waves (related to "exposure")[4], trophic state of the water and bottom type (variables that will affect how sensitive the environment will be to farm effluents)[5], system type (technical specifications of the farm)[6], integrated potential (potential to establish integrated aquaculture to enhance sustainability of farms)[7], feed and seed source (relates to ecosystem effects)[8], product destination (relates to carbon footprint of the sector)[9], user conflicts (conflict with other users of the lease area, e.g. fishers)[10], escapes (one of the major problems at exposed sites is physical damage to fish cages and related fish escapes)[11], references from the literature[12] and status (whether offshore aquaculture is in planning stages or exists)

Country	Species and production level	Site exposure level	Currents and waves	Trophic state of the water and bottom type	System type	Integrated potential	Feed and Seed source	Product destination	User conflicts	Escapees	References	Status
China - Tropical China (4 Southern provinces)	~900 offshore cages in the Chinese tropics. Main Species are: cobia, amberjack, Japanese seaperch, red seabream, black porgy, tongue sole (Indigenous), red drum, derbio and southern flounder (Introduced). Production is expected to reach 500 000 mt by 2010.	Mostly inside the 40 m isobath. Many in more sheltered environments. Some exposed to typhoons and full open ocean conditions – only 13 submersible and 36 other offshore cages were deployed by 2000.	Farms are located from several hundred to several thousand metres offshore but mostly in shallow waters (15–20 m). Systems were tested at currents of 0.5–2 knots and submersible systems withstood typhoons with waves of >5 m.	Mostly eutrophic. In Hainan Island Province water quality is better than the mainland. Many of the bays where exposed and semi-exposed farms are located suffer from and contribute to coastal pollution. Some farms are subjected to runoff. Bottom is mostly muddy. Especially near estuaries and in sheltered bays. Some sand and silt but in shallow seas under further offshore cage systems - mud flats.	Six main cage types – HDPE circles (first imported and then adapted) are now locally produced and are commonest. floating rope cage, metal gravity cage, dish shape submersibles (imported and then adapted from Oceanspar, PDW submersible (for flatfishes), SLW submersible (spherical or cylindrical). In Hainan, 800 submersible HDPE cages have a 500 m^3 volume and produce 20–40 mt of Derbio annually.	Mainly seaweed-shellfish cultures.	Feed is mostly trash fish. Seed is mostly locally produced in hatcheries but some is imported or caught.	The more expensive, offshore grown species are mostly shipped to Japan, Taiwan Province of China, Hong Kong SAR, USA, Canada and Europe.	–	There is little quantitative information on the numbers of animals that escape from aquaculture operations.	Lovatelli *et al.* (2008); Feng *et al.* (2005); Cao *et al.* (2007).	Most farms are operational. Many of the further offshore projects in planning stages.

TABLE 2 (CONTINUED)

Country	Species and production level	Site exposure level	Currents and waves	Trophic state of the water and bottom type	System type	Integrated potential	Feed and Seed source	Product destination	User conflicts	Escapees	References	Status
Taiwan, Province of China	Cobia indigenous 3 000 mt in 2001, 1 000 mt in 2002.	Family owned operations are protected in bays. company owned – in open water (Liu Chiu) or protected lagoon (Pengu)	Penghu is sheltered - 0.8–1.7 m waves. Liu Chiu is in higher energy environments and waves surpass 3 m. Tidal currents of up to 2 knt in Taiwan, Province of China strait.	The water is mostly oligotrophic. Bottom: Sand/Mud in sheltered inshore areas. Mud/silt in offshore farms in Taiwan, Province of China Strait. Some coral reefs in Penghu, including a nearby MPA (Chinwan).	Square net cages in Penghu. Round HDPE cages in Liu Chiu.	In Penghu cobia are integrated with oysters.	Local seed. Pellet feed – partially locally made.	Japanese or local markets.	–	No record but some damage was caused to cages by typhoons. Other damages by poaching and vandalism.	Liao *et al.* (2004); Liao, 2000; Latanich, 2009.	Operational
Viet Nam	Cobia (10 000 mt), red drum and seabass. Some *Kappaphycus* is being cultivated in semi-protected areas using floating rafts.	Semi-protected in lagoons and estuaries. 1 000 mt in 25 circle cages in Nha Trang Bay.	The South China Sea has strong bottom currents but waves get high only during typhoons.	Coastal waters strongly affected by terrestrial runoff. Mostly muddy bottoms.	Norwegian imported and locally made round HDPE cages.	Some siganids are raised in Viet Nam, which can potentially be integrated with predators for cage cleaning.	Cobia, red drum and seabass seeds are hatchery reared. Almost all feed is trash fish.	Export to Japanese and US markets.	–	No record	FAO NASO, Marine Farms Ltd.; Merican, 2006, Tong, Hoang and Nguyen, 2005.	Coastal and protected cages operational. Exposed cages planned.
Mauritius	Seabream and seabass, red drum and siganids. All indigenous. 370 mt of red drum produced in 2006. total Expected to reach ~1000 mt by 2010	Semi-protected – in a lagoon.	Relatively low waves and currents in the lagoon.	Oligotrophic waters. bottoms sandy or sand/silt.	Round HDPE cages in the lagoon.	Siganid culture can be integrated to clean cages from algae.	Local seed. Use of local trash fish for feed.	Export. Mainly to Japan	–	No record	Ministry of Agro-Industry and Fisheries of Mauritius (2007).	Operational

TABLE 2 (CONTINUED)

Country	Species and production level	Site exposure level	Currents and waves	Trophic state of the water and bottom type	System type	Integrated potential	Feed and Seed source	Product destination	User conflicts	Escapees	References	Status
Reunion and Mayotte (France)	Drum and cobia (indigenous) – 200 mt in Mayotte in 2007. 45 mt of drum	Mayotte farm is semi-protected, within the Mayotte lagoon. Reunion farm across from St. Paul is in open water. Both are impacted by typhoons.	–	Water is oligotrophic and bottoms are mostly sandy.	N/A	N/A	Seed imported from Taiwan, Province of China.	Export to EU, mainly France.	–	No record of escapes or damage to cages.	Dabaddie (2009).	operational. Target is 1›000›mt
Belize	Cobia (future plans - Pompano) indigenous. ~300 mt in 2007. Projected to reach 5 000 mt in 2011.	Semi-Protected in barrier reef lagoon, but still exposed to hurricanes.	Cages located in areas with >0.1m/sec currents for nutrient dispersal.	Water: oligotrophic. Bottom: sand with some corals.	Gravity HDPE cages.	N/A	Seed initially from the United States of America, but expected to be local from 2009. Pellet feed	Export to the United States of America.	Possible friction with marine-mammal tourism (manatees)	No record yet.	Benetti *et al.* (2006), Benetti *et al.* (2008).	Operational
Bahamas and Puerto-Rico	Cobia and snapper (*Lutjanus analis*). 50 mt each farm (demonstration phase) but with plans to expand to 750 mt.	Exposed site in Puerto Rico. Semi-protected in Bahamas.	Current - 0.5–1.5 km. depth – 25–30 m.	Water oligotrophic. Bottom: sand (no coral reefs nearby).	Submersible nets ystems 3000 by Oceanspar.	N/A	Fingerlings provided by foreign hatcheries. Imported pellet feed.	Export to the United States of America.	N/A (submersible cages).	Shark attacks led to escapes in all Caribbean region operations.	Benetti *et al.* (2008).	Experimental phase
Hawaii	Pacific threadfin (Moi) in Oahu – 750 mt. Plans to expand to 7 000 mt. *Seriola rivolina* in Kona – 650 mt.	Exposed sites - 2 nm off the coast at Oahu and 0.5 nm off the coast at Kona at 30 m depth.	Up to 1.5 km at Kona.	Oligotrophic	Submersible cages – Oceanspar. Plan to deploy 12 Oceanspheres by 2014.	N/A	Local seed. Imported pellet feed.	Either local markets (Moi) or mainland United States of America.	–	Several thousand fish escaped from Kona Blue Farms in Hawaii (USA).	Borgatti and Buck (2004, 2006).	Operational

and Mauritius, have small governmentally backed pilot operations which are only semi-commercial. In December 2007, the Ministry of Agro-Fisheries of Mauritius identified numerous sites suitable for offshore aquaculture and estimated a production potential of 15 000 tonnes, however this was not translated to the development and installation of farms. Such surveys are not uncommon; as several tropical countries (including India; Bhat and Vinod, 2008) have mapped and demarcated possible sites suitable for offshore mariculture and declared plans for production. Despite this, many still seem to wait for an economic incentive that would establish the profitability of the business. In Bangladesh, the poorest of Asian countries, we may find such an example, of the gap between the only available resource – the sea itself, and the required additional resources. The Bangladesh fishery department identified the potential of the aquaculture industry and requested aid, naming their major constraints: a lack of awareness, technology, infrastructure, hatcheries, skilled manpower, markets, legislation or financing (Kabir, 2006). It stands to reason therefore, that until external drivers force initial investment costs downwards and enable a sufficient amount of knowledge to accumulate, offshore aquaculture will continue to stall or grow slowly in these regions. It seems, however, that excluding Southeast Asia, at the onset of the second decade of the 21st Century tropical countries are still dragging their feet with regard to offshore mariculture development.

RECOMMENDATIONS

- Need to lobby for greater development of offshore aquaculture, which should address permitting issues and include government subsidies and financial support.
- To enhance the sustainability of offshore aquaculture, need to select species on the basis of trophic level, with preference for herbivorous fish, shellfish and algae.
- Proper site selection guidelines, using models where needed; prefer sites with good flushing rates to maximize fish health; need to balance depth with ecological impact/logistical considerations.
- Must balance distance from shore with carbon footprint/tourism/NIMBY/ distance travelled by farm workers.
- Site preference – as close as possible to hatchery, processing plant, marketing; as far as possible from ecologically sensitive areas (reefs, seagrass beds, etc.); consider proximity to other farms (flow disruption, disease, nutrient buildup).
- Need to develop suitable and feasible protocols for monitoring farm management and the environment around the farms.

CONCLUSIONS

Tropical offshore mariculture is a growing industry with much to offer. When comparing offshore mariculture to land-based aquaculture, the potential benefits clearly outweigh the costs in terms of profitability, land use and ecosystem preservation (Troell *et al*., 2003; Bennetti *et al*., 2006). That said, in the tropical regions the benefits and costs are not strictly comparable, since pond aquaculture can be (and is) developed as a low-tech, extensive agricultural system that benefits the rural poor, whereas offshore mariculture is restricted to corporate initiatives capable of large capital investments, technological imports, and the assumption of significant risk. The ecological effects of intensive coastal mariculture have reduced its potential for expansion and fostered increasing opposition to existing projects. While offshore mariculture is more costly, risky (as a result of high exposure to the elements) and logistically difficult than coastal mariculture, properly planned offshore facilities can avoid many of the environmental problems of sheltered systems while maintaining high production levels. The growth of this industry in the tropics will require major investment of capital, knowledge and planning resources to underdeveloped nations. Moreover, it is important to examine the suitability of current commercial species and new species for offshore rearing and to explore the feasibility of polyculture and integrated aquaculture systems in highly-exposed sites.

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The development of offshore aquaculture: an economic perspective

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ABSTRACT

This study offers an economic perspective on the potential future development of offshore aquaculture and its economic effects. Offshore aquaculture is still in its infancy. There is little publicly available economic information about offshore operations on which to base empirical economic analysis. More importantly, the limited experience with offshore aquaculture to date is not necessarily representative of the technologies, species and locations which will characterize offshore aquaculture in the future. Future offshore aquaculture will likely occur in many different environments, using many different technologies, at widely varying scales, with widely varying markets and costs. Given these uncertainties, this study does not offer definitive conclusions about the potential for offshore aquaculture and its economic effects. Rather, it focuses on presenting a theoretical economic framework for thinking systematically about economic questions associated with offshore aquaculture.

<u>Economic potential for offshore aquaculture</u> – Offshore aquaculture will develop to a significant scale if and only if it is profitable. Supply and demand analysis provides a useful theoretical framework for thinking about the conditions under which offshore aquaculture will be profitable, and why and how these conditions may change over time. In general, capital and operating costs are likely to be higher for offshore aquaculture than for inshore aquaculture. However, there may also be offsetting cost advantages to the extent that better water quality improves survival or growth rates or that larger scale operations are possible. Importantly, two of the largest costs of aquaculture – feed and juveniles – are essentially the same for offshore aquaculture as for inshore aquaculture. Because of higher capital and operating costs, offshore aquaculture may not be economically viable for species for which wild fisheries or inshore aquaculture can meet demand at prices lower than those needed for offshore aquaculture to be profitable. However, offshore aquaculture which is not currently profitable may become profitable in the future as a result of three broad mechanisms:

- *Increasing demand for fish*, causing prices to rise to levels which make offshore aquaculture profitable.

- *Declining costs of offshore aquaculture*, making offshore aquaculture more profitable.
- *Increasing costs and/or reduced production from wild fisheries and inshore aquaculture*, making them less able to meet demand.

Offshore aquaculture can be economically viable even if costs are higher than for inshore aquaculture and wild fisheries. What matters is not whether inshore aquaculture and wild fisheries can produce fish at a lower cost, but whether they can produce enough fish at a lower cost to keep prices below levels at which offshore farming is profitable. At its current scale and given current technology, offshore aquaculture is a relatively high-cost way of growing fish. Currently, offshore aquaculture is probably able to compete with inshore aquaculture only under limited circumstances, such as the following:

- When offshore weather and wave conditions are relatively mild, reducing the costs of building and operating offshore facilities relative to inshore aquaculture.
- When offshore farms enjoy significantly better water conditions than inshore farms, enabling faster growth or better survival.
- When offshore farms are able to supply market niches which cannot be supplied by inshore farms, for reasons such as lack of suitable sites, regulatory constraints, and transportation costs.
- When offshore farms are able to take advantage of cost-lowering synergies with other facilities or activities such as existing inshore farm facilities or offshore oil rigs.

Over time, however, the economic potential for offshore aquaculture is likely to grow, for several reasons:

- Growing population and income and changing tastes will increase world demand for fish, raising prices.
- The relative cost of offshore aquaculture, in comparison with inshore aquaculture, will decline, due to technological advances, experience and economies of scale.
- The relative values of competing uses of potential inshore farming areas will increase, reducing the availability of those areas for inshore farming.

Among the most important factors affecting the economic potential for offshore aquaculture will be:

- The extent and pace of technological development in areas such as remote monitoring, remote feeding, cage construction and the extent to which these technological developments can reduce costs and risks of offshore farming.
- The extent to which offshore farms are able to achieve better growth rates and survival than inshore farms.
- The extent to which offshore facilities face fewer conflicts with other activities than inshore farms.
- The extent to which offshore farming is able to develop to a level at which it begins to realize significant economies of scale and to spur the development of key supporting industries such as hatcheries, veterinary services, cage manufacture and processing.
- The extent to which enabling regulatory frameworks establish clear, stable and timely processes for permitting and regulating offshore farms.

It is possible to envision a very wide variety of types of offshore aquaculture developing in the future. Many different species could potentially be farmed profitably offshore, in many different places, using many different kinds of technologies, for many different markets. There is no single answer about the economic potential for these many types of offshore aquaculture and when they might become profitable. The answers vary for different species, locations and technologies. The world offshore aquaculture industry is still in its infancy. There has been only limited experience on which to judge its future potential. It is impossible to know with certainty what the long-run economic opportunities for offshore aquaculture may be. But it is reasonable to assume that they are real and substantial.

Market effects of offshore aquaculture – The market effects of offshore aquaculture will in general be similar to the market effects of any expansion of aquaculture production. These include effects on prices received by inshore farmers and fishers (and correspondingly on prices paid by consumers) and longer-term expansion of market demand potentially benefiting all producers. In the short run, growth in offshore aquaculture production will tend to lower fish prices by increasing the supply of fish, harming fishers and inshore farmers, but benefiting consumers. The extent to which different countries benefit from or are harmed by offshore aquaculture will depend on the extent to which their citizens are consumers of fish grown offshore, producers of fish grown offshore, or producers of fish which compete with fish grown offshore. Over the longer run, however, growth in offshore aquaculture production will tend to increase the world demand for fish as consumers become more familiar with fish; as fish become available in more locations, at more times and in more product forms; and, as offshore fish farmers engage in systematic marketing to expand demand. Increasing demand will tend to offset the effects of increasing supply on prices.

Economic impacts of offshore aquaculture – In general, because of the more difficult working conditions offshore and the higher cost of transporting workers to offshore facilities, offshore fish farms are likely to be more mechanized and have fewer people working on the farm sites per metric tonne of production than inshore farms growing the same species. Offshore aquaculture, like other kinds of aquaculture, will create jobs and income in many more places and industries than on fish farms. These will include both industries which supply fish farms with inputs (juveniles, feed, cages, veterinary services, etc.), as well as, industries which process, transport and distribute fish grown offshore. Thus, the potential economic impacts of offshore fish farming are much larger than the jobs and income created directly at offshore farming operations. These economics impacts will be spread over a far greater geographic area than the communities where fish farms are located or from which they are supported – and may extend too many other countries.

Economic implications of government policies for offshore aquaculture – Government leasing and regulatory policies are critically important for offshore aquaculture. Offshore aquaculture cannot and will not happen unless governments establish leasing and regulatory policies which give fish farmers the opportunity and incentive to invest in offshore fish farming. Just as importantly, without the potential for eventual economic benefit, companies will not invest in research on how to address potential engineering or other challenges for offshore aquaculture. Until actual offshore operations are in place, there is no opportunity to learn from experience about how to address the challenges. The surest way to ensure that no solutions are found for these challenges is to ban offshore aquaculture until they are found. The surest way to ensure that no benefits are realized from offshore aquaculture is to ban offshore aquaculture until the benefits are proven.

Having an enabling regulatory policy does not in any way imply that offshore aquaculture should not be regulated or that the environment should not be protected. On the contrary, strict regulations and environmental protection is not only consistent with, but essential for successful offshore aquaculture development. What is needed is not absence of regulation but clear, consistent and efficient regulation that provides clear guidelines for where and how offshore aquaculture will be allowed and addresses regulatory goals in a cost-effective way. To the extent practical, government leasing and regulatory policies should be clear and stable and should avoid unnecessary delay, site leases should be well defined and transferable and policies should regulate outcomes rather than inputs.

To the extent practical, regulatory institutions for offshore aquaculture should have clear responsibility and authority, should consider both costs and benefits of offshore aquaculture and should consider and balance local, regional and national interests.

Recommendations for FAO – FAO should encourage and facilitate the development of offshore aquaculture, but should not oversell it. The true test of whether, where and when offshore aquaculture is a good idea is the market. Although it seems highly likely that eventually large-scale aquaculture production will occur offshore, helping to meet food demands of a larger and wealthier world population, this does not necessarily mean that offshore aquaculture is currently economically viable on a large scale. That has yet to be demonstrated. At this stage the most appropriate strategy for FAO is to continue to collect and disseminate information about the potential for offshore aquaculture and to encourage its Member states to create enabling regulatory frameworks under which investors can test that potential. Probably the most effective role FAO can play is in helping governments (as opposed to the private sector) obtain information they need to understand the potential of offshore aquaculture and to plan for and promote its responsible development. FAO is well suited to help provide this information by doing things it does regularly and well, including support of technical studies by experts; hosting meetings for sharing information among technical experts and government officials; and facilitating efforts to discuss and establish consensus on international issues related to offshore aquaculture, such as the development of aquaculture in international waters.

INTRODUCTION

As aquaculture expands worldwide, there is growing interest in farming fish[1] further offshore. Although there are many technological and economic challenges in farming in more exposed environments, there are also many potential benefits, including more space, fewer conflicts with other uses of the marine environment and reduced impacts on the marine environment.

The development of offshore aquaculture raises many technical, biological, spatial, economic, legal, policy and livelihood issues of importance to FAO and its Member countries. FAO is conducting a project to collect global information on the potential for offshore aquaculture and to consider the issues which it raises. This study is one of a number of technical reviews conducted for this project.

This study offers an economic perspective on the development of offshore aquaculture and on selected issues raised by offshore aquaculture. It focuses on the question: *Why and how will offshore aquaculture develop and what economic effects will it have?*

Offshore aquaculture is still in its infancy. There is little publicly available economic information about offshore operations on which to base empirical economic analysis.

More importantly, the limited experience with offshore aquaculture to date is not necessarily representative of the technologies, species and locations which will characterize offshore aquaculture in the future. Future offshore aquaculture will likely occur in many different environments, using many different technologies, at widely varying scales, with widely varying markets and costs.

Given these uncertainties, this study does not offer definitive conclusions about the potential for offshore aquaculture and its economic effects. Rather, it focuses on presenting a theoretical economic framework for thinking systematically about why and how offshore aquaculture will develop and what its effects will be.

Challenges for economic analysis of offshore aquaculture

There are several fundamental challenges in economic analysis of how offshore aquaculture will develop and what its effects will be.

[1] Throughout this study, the term "fish" is used to refer to all potential aquaculture products, including finfish, shellfish, and marine plants.

First, as noted above, offshore aquaculture is still in its infancy. Only a tiny fraction of world marine aquaculture production currently occurs "offshore" in relatively exposed ocean environments. The limited experience with offshore aquaculture to date is not necessarily representative of the technologies, species, and locations which will characterize offshore aquaculture in the future. It is difficult to predict accurately how, when and where offshore aquaculture will develop in the future. The farther one looks into the future, the less certain one can be about the key factors which affect the development of offshore aquaculture: what aquaculture technologies may evolve, what the resulting cost structures may be for onshore, nearshore and offshore aquaculture and what prices of fish and other competing proteins will be.

The challenge of predicting why and how offshore aquaculture will develop and what effects it will have is analogous to the challenge one would have faced in 1929 – at the time of Lindbergh's flight across the Atlantic – in predicting why and how large-scale intercontinental air travel would develop and what effects it would have. The industry knows that offshore aquaculture is technically feasible. It seems likely that it will eventually occur on a large scale, driven by growing demand for food and fish, the limits to other ways of expanding food and fish production, and rapid and dramatic technological advances. What it is not known is what it will look like – any more than we could have envisioned 747s and Heathrow Airport at the time of Lindbergh's flight.

A second challenge for the economic analysis of offshore aquaculture is its likely future diversity. As with coastal marine aquaculture, many different species may be farmed, including finfish, shellfish and plants. Production may occur in many different environments, from tropical to subarctic, at widely varying distances from shore, with widely varying wind and wave conditions. Production may occur using many different technologies, at widely varying scales. Markets and costs may vary widely between species, regions, technologies and scales of production.

Thus, there is not a single answer about how offshore aquaculture may develop and what its effects will be, but rather many answers. It is as difficult to generalize about what "offshore aquaculture" will look like or what its effects will be as it would be to generalize about what "freshwater aquaculture" or "coastal marine aquaculture" look like or what their effects are.

A third challenge for the economic analysis of offshore aquaculture is that why and how offshore aquaculture develops and what its effects will be will depend critically on how it is regulated. How offshore aquaculture is regulated will directly affect where, how, when and at what cost it occurs. Regulatory regimes for offshore aquaculture may differ widely between countries – encouraging its growth in some countries and discouraging its growth in others. Thus, part of the answer to the question of why and how offshore aquaculture will develop and what its effects will be depends on how countries want offshore aquaculture to develop and what effects they want it to have.

Given these three broad challenges, this study does not offer definitive conclusions about the future development of offshore aquaculture and its economic effects. Rather, it frames a way of looking at economic questions raised by offshore aquaculture and offers general conclusions about the answers to the questions.

Defining "offshore aquaculture"

There is no commonly accepted definition for the term "offshore aquaculture." It is defined sometimes in terms of distance from shore, sometimes in terms of environmental conditions such as water depth or wave size or expected intensity of storms and sometimes in terms of legal jurisdiction. In theory, it could be defined in terms of a combination of these characteristics.

It would be difficult to arrive to a single definition of "offshore aquaculture" which would be useful for all purposes. Where it would be most useful to draw a dividing line between "inshore" and "offshore" aquaculture may vary depending on whether we are studying technological issues, environmental effects, or regulatory issues. Similarly, where it would be most useful to draw any of these dividing lines may vary between different countries and/or geographic regions.

For the purposes of this study, we define "inshore" and "offshore" aquaculture as follows:

Inshore aquaculture: Aquaculture in relatively protected locations close to shore.

Offshore aquaculture: Aquaculture in relatively exposed locations farther from shore.

These simple definitions suffice for addressing the broad economic questions considered in this study.

Fundamental conditions for the development of offshore aquaculture

It is assumed that two fundamental conditions must hold for the development of offshore aquaculture to a significant scale, which we refer to as the "economic condition" and the "political condition."

Economic condition: Offshore aquaculture will be developed to a significant scale only if it is profitable.

As with any other economic activity, private sector investors will not invest in offshore aquaculture unless they *expect* it to be profitable, and they will not continue to invest in it unless it actually *is* profitable.

In theory, unprofitable offshore aquaculture could develop if governments were willing to subsidize it, or invest in and operate government-owned offshore farms. Certainly, governments may invest in or subsidize experimental or small-scale offshore farming projects for purposes of research, demonstration, or pilot economic development programmes. However, it is assumed that most governments will not subsidize or invest in unprofitable offshore aquaculture at a large scale, partly because there would be little reason to do so and partly because they would not be able to afford doing it.

Political condition: Offshore aquaculture will develop only where there is an enabling regulatory framework which allows investors to undertake projects with a reasonable expectation that their investments in the farm and their fish will be secure and a reasonable degree of certainty about how the operation will be regulated.

Put simply, offshore aquaculture will not happen unless governments create the regulatory conditions under which it can happen. This same "political condition" holds for any economic activity and helps to explain the lack of investment and economic growth in countries with unstable political conditions and/or legal systems. We are not used to thinking about the importance of this "political condition" in countries with developed and stable political and legal systems, including property rights. But even in these countries, it is crucially important for economic activities in offshore waters where rights and conditions for economic activities are not yet defined.

Assumptions about offshore aquaculture

Much of the analysis in this study is based on four assumptions about how offshore aquaculture will *generally* differ from inshore aquaculture. The author assumes that in general, for any given geographic region, species and scale of operation, with currently available technologies, in comparison with inshore aquaculture: (1) offshore aquaculture will face a more challenging physical environment; (2) offshore aquaculture will have higher capital and operating costs per kilogram of production; (3) offshore aquaculture will have fewer significant effects on the marine environment; and (4) offshore aquaculture will create less potential for conflict with other users of the marine environment.

It is not assumed that these assumptions will always be true for all regions or species, only that they are generally likely to be true. Below, each assumption is discussed in greater detail.

1. Offshore aquaculture will face a more challenging physical environment – By definition, it is assumed that offshore aquaculture will occur in relatively exposed locations farther from shore. In general, these locations will have greater water depth and larger waves, posing greater challenges for the design of cages and feeding systems which can withstand these conditions. They will also be located at greater distances from shore-based support facilities, increasing the challenges of installing and operating farms, including stocking, feeding, monitoring and harvesting fish.

2. Offshore aquaculture will have higher capital and operating costs per kilogram of production – Capital costs will generally be higher because anchoring systems must be designed for greater depths and cages must be designed to withstand bigger waves. Operating costs will generally be higher because of the greater distances from shore-based facilities and the more challenging physical environment in which work must be done.

Note that the assumption is that offshore farms will have higher costs than inshore farms *with currently available technologies, for farms of a given scale*. As it will be discussed, it is possible that the relative costs of offshore farms could be lower with future (still-to-be-developed) technologies, or that large-scale offshore farms might benefit sufficiently from economies of scale to have lower units costs than smaller-scale inshore farms. In addition, if growth rates or survival rates are better at offshore farms, this would help to offset the relative operating cost differential of offshore farms.

A simpler basis for the assumption that offshore aquaculture will have higher costs is that most marine aquaculture to date has occurred inshore. If offshore aquaculture were possible at lower relative costs, it is likely that it would have developed to a relatively greater extent.

3. Offshore aquaculture will have fewer significant effects on the marine environment – By "significant" effects we mean effects which are measurable and which have measurable effects on the ecosystem. It is assumed that these effects will generally be fewer because with deeper water and stronger currents waste products will be dispersed over a greater area and are less likely to be sufficiently concentrated to have significant effects on the environment.

4. Offshore aquaculture will create less potential for conflict with other users of the marine environment – In general, diversity and intensity of other uses of the marine environment which might conflict with offshore aquaculture is likely to be relatively higher inshore, including in particular uses such as recreation, scenery (views of the coast enjoyed by local residents and tourists) and small-boat travel. Of course, there may also be conflicts with other uses occurring farther offshore, such as commercial fishing and larger-boat coastal navigation. It is only assumed that conflicts will generally be fewer for offshore aquaculture – not that this will be the case always or everywhere.

BASIC ECONOMICS OF AQUACULTURE

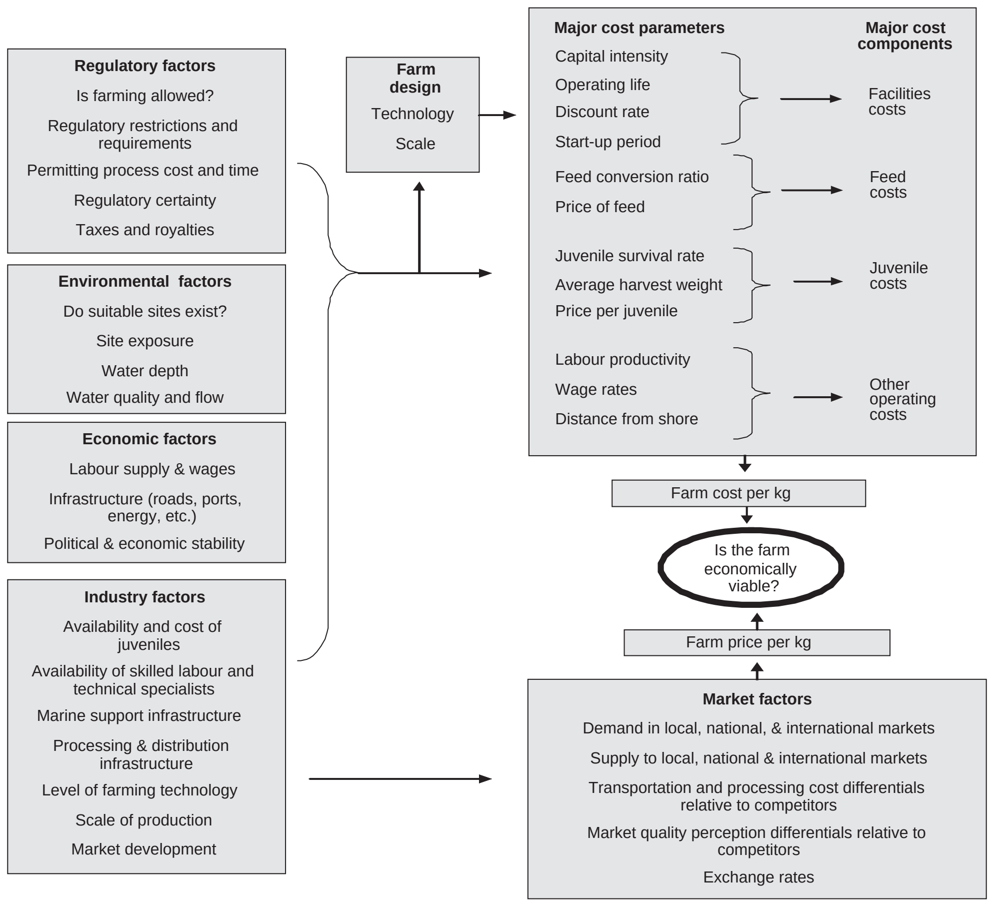
This paper begins by reviewing basic economics of aquaculture: how different factors affect costs, revenues and profitability or "economic viability" of a fish farm. To simplify the discussion, all costs and revenues are expressed on a per kg basis. This requires converting all costs and revenues incurred at different times – including one-time investment costs – into comparable costs and prices per kg.[2]

Figure 1 provides a conceptual framework for thinking about factors affecting the economic viability of a fish farm in a given location growing a particular species of fish. A fish farm is profitable if the average price per kg received for the fish exceeds the average cost per kg of producing the fish.

Major costs of fish farming

The cost per kg of producing fish may be divided into four major cost components: facility costs, feed costs, juvenile costs and other operating costs. Each of these cost components is determined by cost parameters, which are driven in part by the farm design. A wide variety of external factors – shown on the left side of the diagram in Figure 1 – drives both farm design and cost parameters. Some of the same and other external factors drive supply and demand conditions, which determine the price for which the farm can sell its fish.

FIGURE 1
Major factors affecting the economic viability of a fish farm



[2] A fish farm incurs costs and receives revenues over time. Prior to earning any revenues, a fish farm incurs initial one-time costs of planning, permitting and capital investments for cages and other facilities. These are followed by further investments in juveniles and feed. After the first grow-out period, the fish farm begins to earn revenues as the first fish are harvested and sold. Over the operating life of the farm, the farm continues to incur additional costs of juveniles and feed, as well as annual operating and maintenance costs. Analysis of the profitability and economic viability of a fish farm requires comparison of the stream of costs incurred over time with the stream of revenues over time. This may be done using standard methods of investment analysis. In general, a farm is economically viable if the net discounted value of expected revenues over time exceeds the net discounted value of expected costs over time (including the risk-adjusted cost of capital). Thus, profitability depends not just on total costs and revenues, but also on the timing of costs and revenues over the life of the farm, and the risk-adjusted cost of capital.

Facilities cost

A marine fish farm requires a variety of capital investments. The most significant investments are typically for cages, boats, feeding and monitoring systems, onshore facilities (docks, storage facilities and offices) and initial project planning (including design and permitting). For the purposes of this discussion, the cost of these investments is referred as "facilities cost." Any given total facilities cost of a fish farm may be converted into an equivalent annual facilities cost per year of production, which may be thought of as the annual equivalent payment that would be required to pay both principle and interest on a loan for the full cost of the investment over the lifetime of the investment.[3]

Facilities cost per kg is equal to:
(Equivalent annual facilities cost per year of production) / (annual production in kg)

The most important factors affecting facilities cost per kg include:

- <u>Capital intensity</u>: the total initial investment per kg of annual production.
- <u>Discount rate</u>: The risk-adjusted opportunity cost of capital for the project. Depending on how the project is financed, this may be either the interest rate which would be charged on a loan for the investment, or the rate of return which could be earned on an alternative investment of equivalent risk. For any given capital intensity, the higher the discount rate, the higher the facilities cost per kg.
- <u>Operating life</u>: the number of years with harvests to which facilities costs may be attributed. For any given capital intensity, the greater the number of years with harvests, the lower the facilities costs per kg.
- <u>Start-up period</u>: the period of time from when investments are made until harvests begins. For any given capital intensity, the longer the start-up period, the greater the facilities costs per kg.

Feed cost

Feed cost is one of the largest components of finfish farming costs. The most important factors affecting feed cost per kg of fish production include:

- <u>Price of feed</u>. This is the price per kg of feed purchased by the farm.
- <u>Feed conversion ratio (FCR)</u>. This is the ratio of the total weight of feed eaten by a crop of fish (from the time they are purchased as juveniles to the time they are harvested) to the weight gained by the fish between stocking and harvest.

Feed cost per kg of fish is equal to:
(Price of feed) x (Feed conversion ratio)

Feed costs per kg of fish vary depending upon the type of feed, species, feeding technology and other factors affecting growth and survival rates of fish, including water quality.

In general, two opposing trends are likely to affect future feed costs per kg for marine aquaculture. The price of feed may increase as rising feed demand puts upward pressure on prices of fish meal and fish oil, which are major inputs to feed production. Rising prices of feed will increase farmers' incentives to reduce feed costs by improving feed conversion ratios. This may be done in a number of ways, such as reducing fish mortality, developing better feeds that fish are able to utilize more efficiently, improving the timing and method of feeding, utilizing more vegetable-based feeds

[3] Financial analyses of fish farms often include "interest" and "depreciation." The concept of annual facilities cost as used here is approximately equal to the sum of interest and depreciation, with the assumption that interest and depreciation are identical for each year of facility life.

and shifting production from carnivorous species to non-carnivorous species. Future trends in aquaculture feeds costs per kg will depend on the relative strength of these opposing trends.

Juvenile cost

Juvenile cost is another important component of marine aquaculture cost. The most important factors affecting juvenile cost are:

- Price per juvenile. This is the delivered cost of individual juveniles purchased from a hatchery.
- Juvenile survival rate. This is the percentage of juveniles which survive to be harvested. It is equal to the inverse of the number of juveniles per harvested fish.
- Average harvest weight. This is the average weight of fish at harvest.

Juvenile cost per kg of fish harvested is equal to:
= (Price per juvenile) * (Juveniles per harvested fish) / (Average harvest weight)
= (Price per juvenile) / [(Juvenile survival rate) * (Average harvest weight)]

Key factors affecting fish farming costs

Fish farming costs vary widely depending upon the species being farmed and where and how it is farmed. In general, however, feed and juveniles represent the largest cost components for most types of finfish farming, while operating costs and facilities costs tend to represent a much smaller share of total cost, even for offshore farms.

This basic fact is important in considering the economics of offshore fish farming and its ability to compete with inshore farming. Although operating costs and facilities costs are likely to be higher for offshore farming, feed costs and juvenile costs are likely to be the same – or potentially lower, if offshore water quality and water flow are better.

The smaller the share of total costs represented by a particular cost element, such as facilities cost, the less significant the effect of an increase in that cost element in its relative effect on total cost. For example, suppose facilities costs and feed costs account for 10 percent and 50 percent of the total cost of an inshore farming operation, respectively. If facilities costs are 100 percent higher for an offshore farm, this represents only a 10 percent increase in total costs – which would be fully offset by a 20 percent decrease in feed costs.

Farm design

Some cost parameters are influenced by the farm design: the technology used by the farm and the scale of the farm. These include capital intensity, operating life, feed conversion ratio, juvenile survival rate and labour productivity. In general, as in other kinds of agriculture, fish farmers face a choice between capital intensity and other cost parameters. By increasing the capital intensity of the farm (which increases facility costs) farmers can achieve better feed conversion ratios, better juvenile survival rates and higher labour productivity (which lowers feed costs, juvenile costs and other operating costs).

The important point to recognize is that cost-minimizing design choices for offshore farming may differ from those for inshore farming and cost-minimizing design choices for offshore farms may differ from those for foreign offshore farms. For example, if labour costs more per hour for an offshore farm than for an inshore farm, an offshore farm is likely to use relatively less labour, thus, reducing the extent to which higher labour costs represent a cost disadvantage.

Regulatory factors

Regulatory factors directly affect the economic viability of fish farming – most obviously by whether farming is allowed at all, but also in numerous other ways.

Regulatory restrictions and requirements may limit farm design choices of scale and technology and may impose additional costs such as environmental monitoring. The permitting process may represent a significant cost which increases with the time required for permitting and the uncertainty associated with the outcome. Regulatory certainty – the likelihood that regulations will stay the same over the life of the farm – affects the risk associated with farming investments and the discount rate for facilities investments. Taxes and royalties represent additional direct costs.

Put simply, to a significant extent, the costs and economic viability of fish farming depends on how it is regulated. Favourable regulation cannot make a fish farm economically viable if environmental, economic, industry and market factors are unfavourable. But unfavourable regulation can keep a farm from being economically viable even if other factors are favourable.

Environmental factors

Key environmental factors affecting economic viability of a fish farm include site exposure, water depth and water flow. Exposure to waves and wind directly determine what kinds of cages and other farm equipment will work and the risks of farm damage and loss of fish. Water depth affects installation costs. Water depth, quality and flow affect feed costs and juvenile costs by affecting fish growth rates and mortality rates. Water depth, quality and flow also affect potential environmental effects of a farm and the extent to which these must be mitigated, either because it is in the farmer's own interest or because of regulatory requirements.

Economic factors

General economic conditions affect the costs and economic viability of a fish farm. Key economic factors include labour supply and wages, transportation infrastructure and availability and cost of utilities. Another critical factor is political and economic stability, including protection of property and basic rule of law.

Industry factors

The costs and economic viability of an individual fish farm are affected by a number of industry factors which depend on the scale and experience of the industry. As the scale of the fish farming industry within a region or nation grows, it creates a demand for specialized aquaculture support activities, such as hatcheries, veterinary services, fish transportation and processing. As the scale of these activities expands, this tends to lower costs and expand the types and scale of farming which is feasible. More generally, experience gained in farming drives technological change. Industry factors may be thought of as "feedback factors" affecting economic viability, in the sense that as an industry grows and gains experience, economies of scale and technological change help to lower costs and further expand the industry.

Market factors

Price is as important as cost to the economic viability of a fish farm. The price per kilogram received by a farm is driven by a wide variety of market factors interacting in complex ways. The effects of these factors can generally be described within the supply and demand framework presented below.

Which market factors are most important depends on the size of the market and the relative scale of competition. If a fish farm is supplying a market or markets which are also supplied with comparable fish of comparable quality from competing sources, the volume of competing supply and the prices offered by competitors are key factors influencing the price received by the farm. Put differently, the price depends on whether the demand for the fish is local, national or international and whether the competing supply is local, national or international.

Different factors also drive prices in the short-term (over the course of one or a few years) than over the long-term (the expected period of operation of a fish farm). In the short-term, prices are driven by the total supply available to the market given current production. Over the longer term, prices are driven by the capacity of producers to expand or contract production in response to higher or lower prices.

In national and international markets, competition typically occurs at the wholesale level, between fish which have undergone primary processing and been transported either to end-market locations or locations where further processing occurs. The price paid to a fish farm is driven not only by the wholesale price, but also by the costs of processing and transportation, which must be subtracted from the wholesale price. Put differently, whether a fish farm can be competitive is determined not just by the cost of growing the fish, but also by the costs of processing the fish and transporting it to markets. In considering whether a particular farming operation can be competitive, an important factor is how both processing costs and transportation costs to markets compare with those of competitors. A higher-cost farm can be competitive if its products can be processed at a lower cost or shipped to markets at a lower cost than for competitors.

Both processing and transportation costs depend in part on the scale of the industry. A pioneer fish farm in a location may face relatively high processing and transportation costs if the fish processing industry and transportation infrastructure is not well developed. As the industry grows in scale these costs may decline significantly, making fish farms relatively more competitive. Thus, some of the industry scale factors which affect the costs of a fish farm also affect the price paid to a fish farm, through their effects on the costs of processing and transportation.

A similarly important factor is the perceived quality of a farm's products compared with competing suppliers' products, as reflected in the relative prices buyers are willing to pay. A higher-cost farm can be competitive if its products can command a higher price than those of competitors.

COMPETITIVE DISADVANTAGES AND ADVANTAGES OF OFFSHORE AQUACULTURE

Relative to inshore aquaculture, offshore aquaculture has a number of potential competitive disadvantages (factors which tend to increase relative costs), but also certain potential competitive advantages (factors which tend to reduce relative costs). Potential competitive disadvantages include:

Greater exposure. Offshore aquaculture faces significant technical challenges and costs of constructing, installing, operating and maintaining cages and feeding and monitoring systems able to withstand wave and wind conditions in an exposed ocean environment. A more exposed environment also adds to the required sizes and construction and operating costs of support vessels. This increase in costs may be significantly reduced where there are synergies with existing or new offshore facilities built for other purposes, such offshore oil platforms or (as envisioned for the future) wave power generation installations.

Higher support transport costs. Offshore farms are (by definition) located farther from shore than onshore farms. In general, this will mean that fish, feed and workers will need to be transported over greater distances, adding to fuel and labour costs. Note, however, that locating a farm farther offshore does not necessarily imply a greater transportation distance, in comparison with available inshore sites. Depending on terrain, infrastructure development and the extent of the existing inshore farming industry, offshore facilities will not necessarily be farther from onshore support facilities such as docks and roads than available protected inshore sites. Put simply, it may be shorter and quicker for a support vessel to travel five kilometres straight out to sea than eight kilometres up the coast or around a cape to the next bay.

Greater water depth. In general water depth is greater for offshore farms, and may in some cases be much greater – adding to the costs of mooring systems.

More difficult working conditions. Offshore farms will likely need to pay higher wage rates for workers able and willing to work in a harsher and riskier offshore environment and able to work with more complex technology of offshore farms. Note, however, that higher wage rates may be significantly offset by use of more capital-intensive and labour-saving technology such as remote feeding and monitoring systems.

Fewer industry-wide economies of scale. The costs of manufacturing cages and offshore feeding and monitoring systems depend upon the scale at which they are produced. Currently, far fewer cages and feeding and monitoring systems are being built for offshore farming than for inshore farming. Over time, as the scale of offshore investment expands, this will help to lower manufacturing costs for offshore cages and feeding and monitoring systems.

Less operating experience. For almost any economic activity, operating experience helps to identify better and cheaper ways to do things. Worldwide, there has been far less experience in building and maintaining offshore farms than for inshore farms. Over time, as more experience is gained with offshore farming, costs are likely to decline at a relatively greater rate for offshore farming than for onshore farming.

Less regulatory experience. In comparison with inshore aquaculture, there is a lack of experience with the regulation of offshore farming. Regulatory frameworks and effective methods for offshore farm monitoring and regulatory enforcement may not be in place. Potential jurisdictional and legal issues may not have been resolved. This lack of experience is likely to increase the difficulty, time, costs and risks associated with applying for offshore sites and meeting regulatory requirements. Over time, as more regulatory experience is gained for offshore farming, these costs are likely to decline until they are comparable with those for inshore farming.

Potential competitive advantages of offshore aquaculture, relative to inshore aquaculture, include the following:

Better water quality. Water quality is critical to successful fish farming. In general, offshore farms will have more water flow than inshore farms. Offshore farms are also less likely to be affected by pollution from land-based sources such as agricultural runoff. Better water quality contributes to better growing conditions for fish and is reflected in better feed conversion and survival rates, lowering costs of feed, juveniles and facilities and other costs (on a per kilogram basis).

Fewer conflicts with other activities. Because of their greater distance from shore, offshore farms are likely to have fewer conflicts with other economic and recreational uses of the environment. Reduced potential for conflicts with other activities may be reflected in fewer restrictions on farm size and greater economies of scale, as discussed below.

Fewer environmental impacts. Because of greater water flow and depth, offshore farms have less potential for concentration in the water or on the ocean bottom of fish faeces, fish feed or other farm residues. There is also less potential for interaction with species migrating close to shore or with concentrations of migrating anadromous fish. Reduced environmental impacts may be reflected in fewer restrictions on farm size and greater economies of scale.

<u>Potential for greater farm economies of scale</u>. Because of the greater availability of suitable large-scale farming sites and the potential for fewer regulatory restrictions on farm size, offshore farms have the potential to be larger, allowing for reduced costs through greater economies of scale.

<u>Potential for shorter distances to markets</u>. Because of reduced conflicts with other activities and greater availability of sites, it may be possible to locate offshore farms closer to markets (such as major cities) than is possible for inshore farming, reducing transportation costs and making it possible for fresher products to be delivered to markets.

WHAT WILL DRIVE THE DEVELOPMENT OF OFFSHORE AQUACULTURE?

> *"Offshore aquaculture is needed and will happen because the world will need more fish and only offshore aquaculture can meet that need."*

This is a familiar and plausible argument for the need for and inevitability of offshore aquaculture. By itself, however, this argument is incomplete. Offshore aquaculture is an economic activity which will be developed to a significant scale only if it is profitable. To understand how and why offshore aquaculture may develop, it needs to be understood how and why offshore aquaculture may become profitable in the future. How will the world's need for more fish, and the capacity of offshore aquaculture to supply that fish, translate into the economic signals that will make offshore aquaculture profitable and spur investment in offshore aquaculture?

A supply and demand modelling framework

Supply and demand analysis – a basic tool of economics – provides a useful framework for thinking about factors that may drive the future growth of offshore fish farming. Below the author first discusses a framework for modelling fish supply and demand. This framework is then used to discuss different mechanisms by which offshore aquaculture may become profitable and grow in scale over time.

Initial assumptions

For simplicity, it is assumed initially that there is only one species of fish and one global market for fish. Fish may potentially be produced in three ways: from wild (capture) fisheries, by inshore farming and by offshore farming. A regulatory framework exists under which investors may obtain secure rights to both inshore and offshore farming sites. Later, the implications of relaxing these assumptions are explored to allow for more species, more farming regions and more markets.

The subsequent discussion is illustrated with a variety of hypothetical supply and demand curves. What matters with these curves is only their slopes (how supply or demand changes as prices change) and their locations relative to each other (for any given price, relative supply or demand from different types of production). The reader should not be overly concerned with other details of how the curves are drawn. The purpose as intended by the author is not to illustrate actual supply or demand curves (which would vary widely for different species and locations) but rather broad economic principles affecting how fish are produced.

Inshore aquaculture supply curve

It is useful to begin the discussion of fish supply and demand with the fish supply curve from inshore aquaculture.

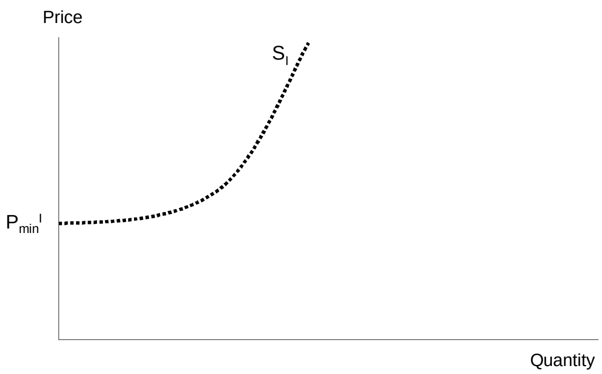
Each existing or potential inshore farming operation has an actual or expected production cost per kilogram. As discussed above, this includes the costs of facilities, feed, juveniles and other operating costs. These costs may vary between farms depending on their location, type of technology, scale of production and the costs of various factor inputs (labour, energy, etc.).

A farm is profitable (economically viable) if and only if the price it receives per kilogram is greater than or equal to the total cost of production per kilogram (including the risk-adjusted cost of capital). Although investors may invest in farms which turn out to be unprofitable, they will not continue to operate them over the long-term unless they are profitable.

As illustrated in Figure 2, the costs of all existing and potential inshore fish farms can be plotted on a graph, with costs per kilogram on the vertical axis and annual production on the horizontal axis arranged in ascending order of cost per kilogram. Plotted in this way, the total costs per kilogram form an inshore aquaculture supply curve. The supply curve shows the potential volume of fish production that would be profitable from inshore farms at any given price per kilogram. Put differently, it shows the price per kilogram that would be required for any given volume of production to be profitable.

Below price P_{min}^{I} no fish could be profitably produced. Above P_{min}^{I}, as the price increases the volume of fish which can be produced profitably increases, as less favourable inshore sites become profitable.

FIGURE 2
Hypothetical inshore aquaculture supply curve



Wild fishery supply curve and offshore aquaculture supply curve

As illustrated in Figure 3, one may also think of "supply curves" for fish from wild fisheries and from offshore aquaculture. Each of these supply curves also shows, for any given price, the total volume of fish that could be profitably produced for that price within a given time period. In other words, it shows the price per kilogram that would be required for any given volume of production to be profitable.

The relative shapes of the three different supply curves reflect the different costs of production for each method of producing fish and how changes in price affect the volume which could be profitably produced. Wild fisheries can produce some fish at prices below the minimum price at which inshore aquaculture is profitable (P_{min}^{I}). However, the total volume of fish which can be produced by wild fisheries is limited by the capacity of the ocean to sustain wild harvests (as well as harvest restrictions imposed by managers). Thus, above a certain volume of fish which can be caught for relatively low cost the supply curve for wild fisheries begins to rise steeply and eventually becomes vertical. Put

FIGURE 3
Hypothetical fish supply curves

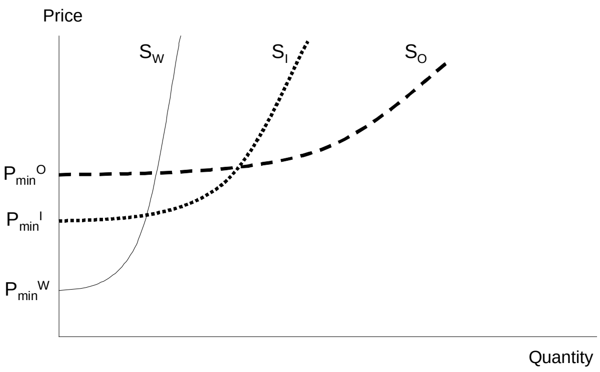


FIGURE 4
Hypothetical total fish supply curve

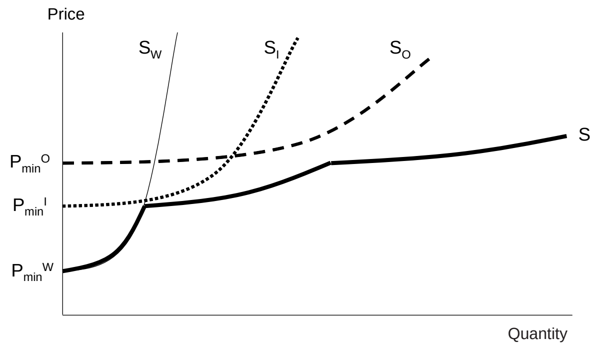
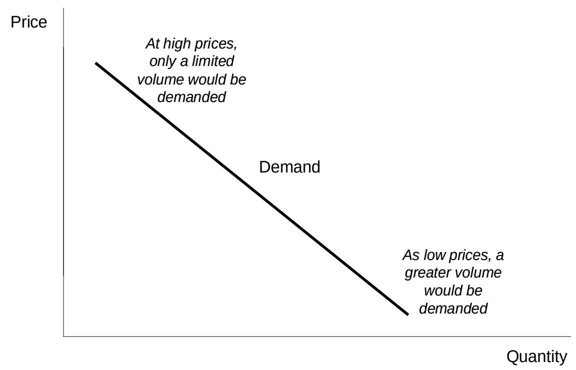


FIGURE 5
Hypothetical fish demand curve



differently, above a certain level of production even high prices cannot call forth additional production from wild fisheries.

In contrast, the minimum price at which offshore aquaculture production is profitable (P_{min}^O) is higher than for inshore aquaculture. However, at prices above this level it is possible to produce large volumes of fish, because of the very large number of sites which become available. Put differently, above a certain price level higher prices can call forth large increases in production from offshore aquaculture.

Total supply curve

As illustrated by Figure 4, the total fish supply curve S is the horizontal sum of the wild supply curve S_W, the inshore aquaculture supply S_I and the offshore aquaculture supply curve S_O. It shows, for any given price, the total volume that could be profitably produced from all three types of production. At low prices (between P_{min}^W and P_{min}^I) supply would come only from wild fisheries. At higher prices (between P_{min}^I and P_{min}^O) supply would come from both wild fisheries and inshore aquaculture. At still higher prices (above P_{min}^O) production would come from wild fisheries, inshore aquaculture, and offshore aquaculture.

Fish demand curve

As illustrated in Figure 5, a hypothetical fish demand curve may also be drawn. The demand curve shows the volume of fish that would be demanded by buyers at any given price per kilogram. Put differently, it shows the price per kilogram that would be required for buyers to demand (wish to buy) any given volume of production.

It is assumed that the demand curve is downward sloping, so that the lower the price, the greater the volume which buyers would wish to buy.[4] Only for simplicity, the demand curve has been drawn as linear (this is not essential to the analysis).

Equilibrium price and quantity

If one plots the fish supply and demand curves on the same graph, as illustrated in Figure 6a, then the price and quantity at which the curves intersect is referred to by economists as the "equilibrium" price and quantity. This is the only price for which the quantity fish producers would be willing to supply equals the quantity buyers would demand.

Economists argue that over time the actual price and quantity will tend to approach the equilibrium price and quantity. At a higher price, buyers would not be

4 In some cases the demand curve may be horizontal or vertical. For example, the demand curve might be represented as horizontal if a large alternative source of production of the same fish (from other regions) were available to buyers at a particular price. In this case, buyer's demand for fish from any given region would fall to zero above the price at which they could get it from other regions – and would become very large at prices lower than the price of fish from other regions. Alternatively, the demand curve might be represented as vertical if buyers always demanded exactly the same quantity of fish regardless of price.

willing to purchase all the fish that farmers would produce, causing a surplus of unsold fish. This would tend to cause the price to fall, which would cause farmers to reduce production and buyers to demand more. Similarly, at a lower price, buyers would want to purchase more fish than farmers would produce. Buyers would tend to bid up the price, which would cause farmers to increase production and buyers to demand less.

FIGURE 6A
Equilibrium price and quantity

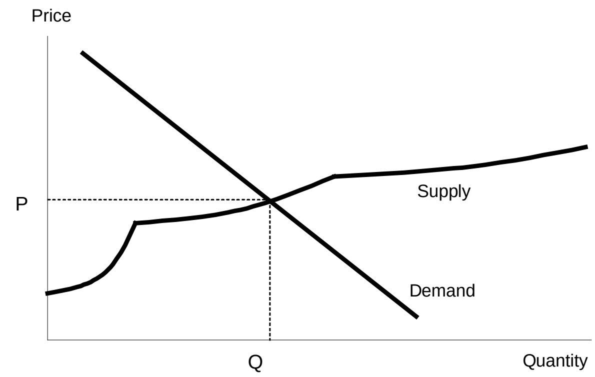


FIGURE 6B
Sources of supply at the equilibrium price

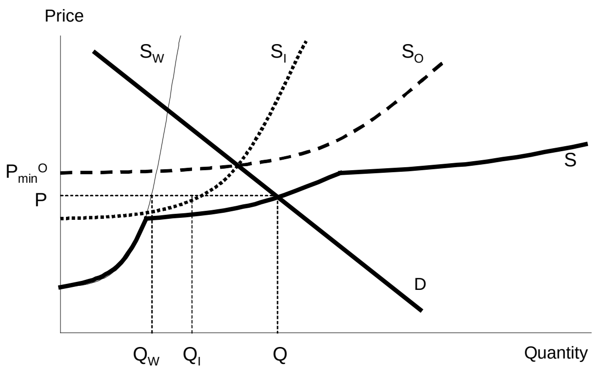


Figure 6b shows the same fish supply and demand curves as Figure 6a, but also shows the supply curves for each of the three methods of producing fish which together result in the total fish supply curve S. At the equilibrium price P, the supply from wild fisheries is Q_W and the supply from inshore fisheries is Q_I, which together add to total supply of Q. At the equilibrium price P, there is no production from offshore farms because – under these hypothetical supply and demand conditions – the equilibrium price is below the minimum price (P_{min}^O) at which any production from offshore aquaculture is profitable.

Mechanisms by which offshore aquaculture may become profitable

Figure 6b illustrates a situation in which the equilibrium price would be too low for offshore aquaculture to be profitable. In economic terms, the demand curve for fish intersects the supply curve at an equilibrium quantity Q which can be met by lower-cost inshore farms. Prices would not rise to the higher level necessary for higher-cost offshore farms to be profitable, because if they did, lower-cost inshore farms would increase production, causing a surplus which would drive prices back down. Put differently, *offshore farming will not be economically profitable if lower-cost inshore farms can fully meet demand at prices below the cost of offshore farming.*

Figure 6b represents the *current* economic situation for offshore production of many species in many countries. Given current demand for fish, current costs of production from offshore farming, and the prices at which fish can be supplied from wild fisheries and inshore aquaculture, offshore aquaculture production is not currently economically viable for many species because demand can be met at lower cost from wild fisheries and inshore production.

However, this does not mean that types of offshore aquaculture which are not currently profitable will never be profitable. Below, the author discusses three potential mechanisms by which offshore aquaculture which is not currently profitable may become profitable over time, by shifting either demand or supply. These mechanisms are summarized in Table 1.

Growth in demand

Higher-cost offshore aquaculture will be able to compete with lower-cost inshore aquaculture and wild fisheries if demand increases sufficiently that the limited volume which can be produced at lower costs from wild fisheries and inshore farming cannot

TABLE 1
Mechanisms by which offshore aquaculture may become profitable

Mechanism	Potential driving factors	Change in demand or supply curves	Effects on price and total fish production	Figures illustrating effects
Growth in demand	Growth in world population Growth in per capita incomes, particularly in newly developing countries Increasing awareness of health benefits of seafood Marketing by the aquaculture industry Constraints to the ability of agriculture and freshwater aquaculture to meet growing food demand, including constraints on availability of land, fertilizer and water	Outward shift in the demand curve for fish	Increase in price Increase in production	7a, 7b
Reduction in offshore costs	Technological advances in cage design, remote control and monitoring technology, anchoring and feeding systems, etc. Reduction in permitting costs and political risks as regulatory frameworks are created and governments and industry gain experience with offshore aquaculture Economies of scale as offshore production increases	Downward shift in the offshore aquaculture supply curve	Decrease in price Increase in production	8a, 8b, 8c
Reduction in alternative supply	Increased demand for other uses of inshore waters resulting in reduced availability of inshore sites Increased regulatory restrictions on inshore farms to reduce environmental impacts	Inward shifts in the wild fisheries and/or inshore aquaculture supply curves	Increase in price Decrease in production	9a, 9b, 9c

fully meet demand. A wide variety of factors could cause a growth in demand for fish. These include (but are not limited to) growth in world population; growth in per capita incomes, particularly in newly developing countries; increasing consumer awareness of health benefits of seafood; marketing by the aquaculture industry; and constraints to the ability of agriculture to meet growing food demand.

FIGURE 7A
Effects of growth in demand

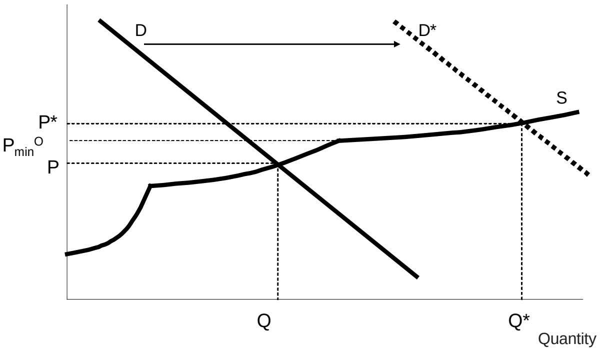
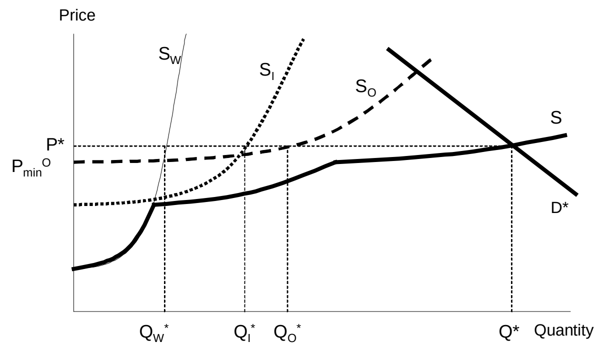


FIGURE 7B
Effects of growth in demand



As illustrated in Figure 7a, growth in demand would cause the demand curve for fish to shift outward from D to D*. This shift in demand causes the equilibrium price to rise from P to P*, above the minimum price P_{min}^O at which offshore aquaculture becomes profitable. Total world fish production rises from Q to Q*.

As illustrated in Figure 7b, at the new equilibrium price P*, quantity Q_W* is produced from wild fisheries, quantity Q_I* is produced from inshore aquaculture, and quantity Q_O* is produced from offshore aquaculture.

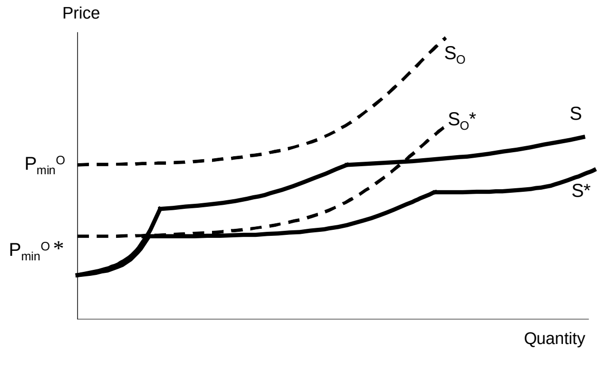
Reduction in offshore costs

Offshore aquaculture will be able to compete with wild fisheries and inshore aquaculture if costs for offshore farming decline sufficiently that offshore aquaculture becomes profitable at prices at which demand cannot be fully met by wild fisheries and inshore farms. Such a reduction in cost might occur, for example:

because of technological advances in cage design, remote control and monitoring technology, anchoring systems, feeding systems, etc.; reductions in permitting costs and political risks as regulatory frameworks are created and governments and industry gain experience with permitting and regulation of offshore aquaculture; and economies of scale as offshore production increases.

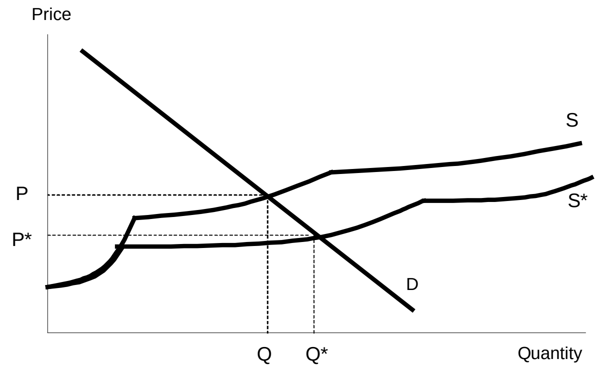
As illustrated in Figure 8a, a reduction in offshore costs would cause the offshore aquaculture supply curve to shift downward from S_O to S_O*, showing that any given volume can be supplied for a lower price. There is a corresponding downward shift in the total supply curve from S to S*.

FIGURE 8A
Effects of a reduction in offshore costs



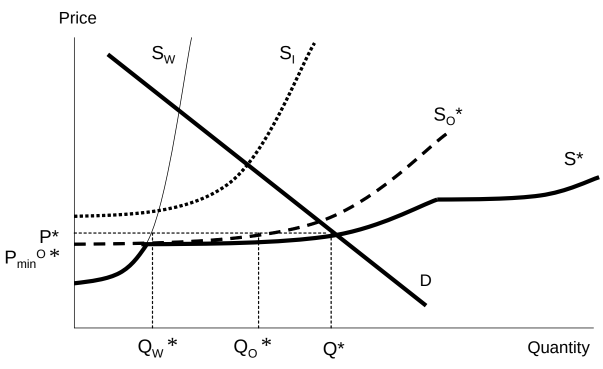
As illustrated in Figure 8b, the downward shift in the total supply curve from S to S* results in an increase in the total equilibrium quantity produced from Q to Q* and a decrease in the equilibrium price from P to P*.

FIGURE 8B
Effects of a reduction in offshore costs



As illustrated in Figure 8c, at the new, lower equilibrium price P*, quantity Q_W* is produced from wild fisheries and quantity Q_O* is produced from offshore aquaculture. There is no production from inshore aquaculture, for which costs have not changed and for which (in this extreme example) the minimum cost of production is now higher than for offshore aquaculture.

FIGURE 8C
Effects of a reduction in offshore costs



Reduction in alternative supply

Offshore aquaculture will be able to compete with wild fisheries and inshore aquaculture if the quantity which can be supplied by wild fisheries and inshore aquaculture at any given price declines sufficiently so that wild fisheries and inshore farms cannot meet demand, causing prices to rise. This might occur, for example, due to increased demand for other uses of inshore waters resulting in reduced availability of inshore sites, or increased regulatory restrictions on inshore farms to reduce environmental impacts.

As illustrated in Figure 9a, a reduction in supply from wild fisheries and inshore aquaculture would cause the wild fisheries supply curve to shift inwards from S_W to S_W* and the inshore aquaculture supply curve to shift inwards from S_I to S_I*. There is a corresponding inward shift in the total supply curve from S to S*.

As illustrated in Figure 9b, the inward shift in the total supply curve from S to S* results in a decrease in the total equilibrium quantity produced from Q to Q* and an increase in the equilibrium price from P to P*.

As illustrated in Figure 9c, at the new, higher equilibrium price P*, quantity Q_W* is produced from wild fisheries, quantity Q_I* is produced from inshore aquaculture,

FIGURE 9A
Effects of a reduction in alternative supply

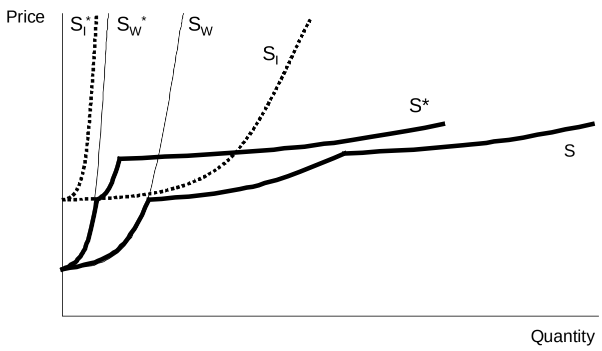


FIGURE 9B
Effects of a reduction in alternative supply

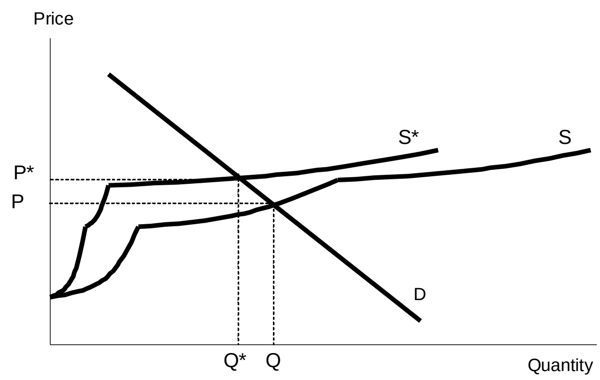
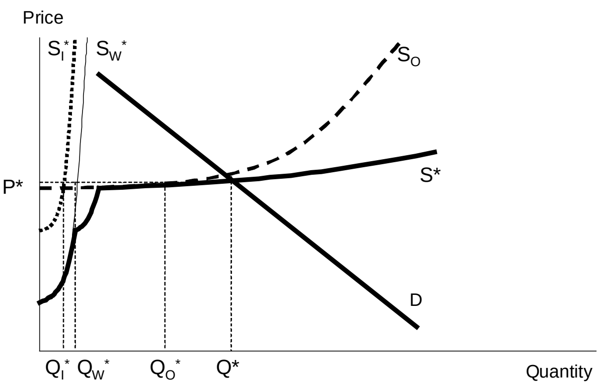


FIGURE 9C
Effects of a reduction in alternative supply



and quantity Q_O* is produced from offshore aquaculture. Production from wild fisheries and inshore aquaculture declines while production from offshore aquaculture increases.

Combined effects of multiple mechanisms

Offshore aquaculture is most likely to become profitable not as a result of any one of the three mechanisms discussed above occurring singly, but rather as a result of all three mechanisms occurring simultaneously. This is illustrated in Figure 10, as a result of simultaneous shifts in demand and supply curves. Growth in demand has caused the demand curve for fish to shift outwards from D to D*. Reductions in offshore costs and reductions in alternative supply have caused the supply curve to shift from S to S*.

The combined result of these shifts is an increase in the total equilibrium production of fish from Q to Q* and (in this example) an increase in the equilibrium price from P to P*. Note, however, that under different assumptions about relative changes in demand and supply the equilibrium price might fall rather than rise.

Modelling supply and demand for multiple regions

Thus far, it has been assumed that there are global supply and demand curves for fish and a global equilibrium price for fish. In reality, of course, the world consists of many different countries (and regions within countries) with widely varying supply and demand conditions for fish. These countries (and regions within countries) represent different markets for fish, which are connected to varying extents by trade.

Suppose two countries (A and B) have different supply and demand conditions for a particular species of fish. As illustrated in Figure 11a, if there is no trade, then the equilibrium price in Country B (P^*_B) would be higher than the equilibrium price in Country A (P^*_A).

As illustrated in Figure 11b, if there is trade between the two countries and the cost of transportation is zero, then the equilibrium price would be the same in both countries – because no buyer would be willing to pay more for fish from one country than the other and no seller would be willing to sell fish for less in one country than the other. In Country A, both the price (P**) and production (Q^{**}_A) would be relatively higher than they would have been without trade. In Country B, both the price (P**) and production (Q^{**}_B) would be relatively lower than they would have been without trade.

As illustrated in Figure 11c, if there is trade between the two countries, but there is a cost for transporting fish between the two countries, then the equilibrium price will differ between countries, but not as much as it would have differed without any trade. The difference between the price P^{**}_B in Country B and the price P^{**}_A in Country A will equal the cost of transportation - because buyers in Country B are indifferent between paying a higher price for domestically produced fish or paying a lower price in Country A plus the cost of transporting the fish from Country A to Country B.

Put simply, costs of transportation (and other barriers to trade) may allow fish prices to differ between countries and region, while the potential for trade limits the extent to which prices differ.

There are in fact significant costs to transporting fish between countries (or regions within countries). In addition, for certain kinds of fish products (particularly fresh products), quality declines with transportation time and distance, which from an economic point of view may also be considered a "cost" of transportation. Countries may also impose a variety of additional barriers to trade, such as tariffs. For all of these reasons, there is not a single global price for fish of a given species. Rather, there are differences in fish prices between countries - although these differences are not as great as there would be without trade.

FIGURE 10
Combined effects of growth in demand, reduction in offshore costs, and reduction in alternative supply

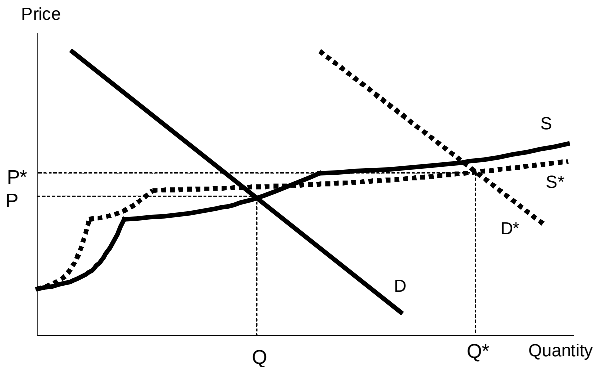


FIGURE 11A
Price and production without trade

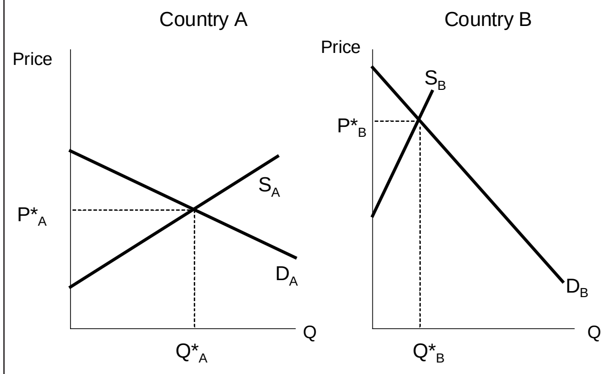
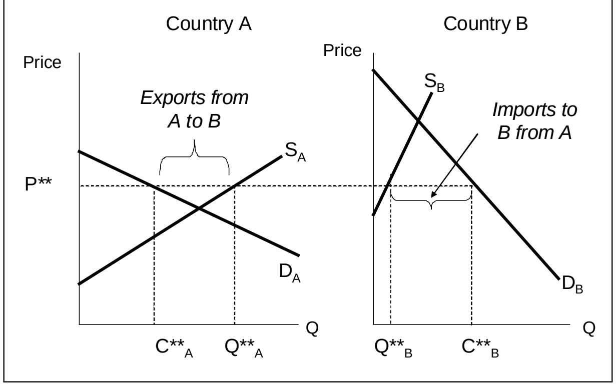


FIGURE 11B
Price and production with trade and zero cost of transportation



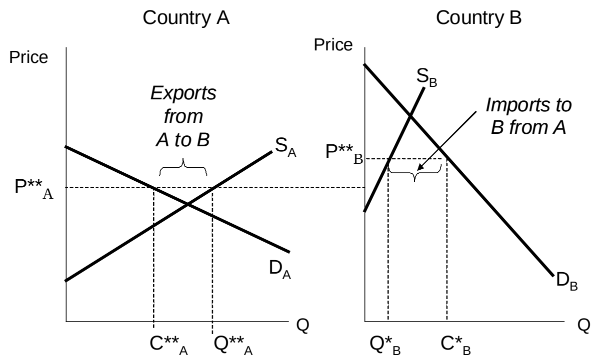
Differences between countries in the economic viability of offshore aquaculture

The economic viability of offshore aquaculture may differ between countries (and regions within countries) for two broad reasons: (a) costs may differ; and (b) prices may differ.

Costs of offshore aquaculture may differ between countries and regions for a variety of environmental, economic and policy regions. In general, all else equal, costs will be lower and offshore aquaculture will be more economically viable in countries and regions in which:

- The offshore environment is more favourable, with shallower water and less exposure to storms, waves, currents, etc.
- The support infrastructure is better developed, with established facilities for juvenile production, fish processing, fish transportation, veterinary services, etc.
- A skilled labour force is available.

FIGURE 11C
Price and production with trade and a positive cost of transportation



- An enabling regulatory system exists with clear regulatory policies.
- There is political and economic stability and the rule of law.

Prices paid for fish grown offshore may differ between countries and regions if demand relative to supply varies between countries and regions. In general, all else equal, prices will be higher and offshore aquaculture will be more economically viable in countries and regions in which:

- Population, income and consumer preferences create strong demand for fish relative to available domestic supply.
- Available domestic supply from wild fisheries and inshore aquaculture is limited.
- Costs are high for transporting fish from other countries or regions, or there are other barriers to trade which add to costs of importing fish.
- Costs are low for transporting fish to other countries or regions and there are few barriers to trade impeding fish exports to other countries which add to costs of exporting fish.

Summary: What will drive the development of offshore aquaculture?

Offshore aquaculture will develop to a significant scale if and only if it is profitable. Supply and demand analysis provides a useful theoretical framework for thinking about the conditions under which offshore aquaculture will be profitable and why and how these conditions may change over time.

In general, capital and operating costs are likely to be higher for offshore aquaculture than for inshore aquaculture. However, there may also be offsetting cost advantages to the extent that better water quality improves survival or growth rates or that larger scale operations are possible. Importantly, two of the largest costs of aquaculture - feed and juveniles - are essentially the same for offshore aquaculture as for inshore aquaculture.

Because of higher capital and operating costs, offshore aquaculture may not be economically viable for species for which wild fisheries or inshore aquaculture can meet demand at prices lower than those needed for offshore aquaculture to be profitable. However, offshore aquaculture which is not currently profitable may become profitable in the future as a result of three broad mechanisms:

- <u>Increasing demand for fish</u>, causing prices to rise to levels which make offshore aquaculture profitable.
- <u>Declining costs of offshore aquaculture</u>, making offshore aquaculture more profitable.
- <u>Increasing costs and/or reduced production from wild fisheries and inshore aquaculture,</u> making them less able to meet demand.

Offshore aquaculture can be economically viable even if costs are higher than for inshore aquaculture and wild fisheries. What matters is not whether inshore aquaculture and wild fisheries can produce fish at a lower cost, but whether they can produce enough fish at a lower cost to keep prices below levels at which offshore farming is profitable. Note that agriculture – farming of wheat, rice, beef, poultry, etc. – occurs worldwide in countries and environments with vastly different costs of production and not just in the lowest-cost countries and environments.

In general, neither inshore nor offshore aquaculture is likely to be profitable for species for which supply from wild fisheries is low-cost, year-round, reliable and abundant relative to demand. However, for species for which wild fisheries are unable to meet these conditions, competitive opportunities will be created for inshore and offshore aquaculture to be profitable.

At its current scale and given current technology, offshore aquaculture is a relatively high-cost way of growing fish. Currently, offshore aquaculture is probably able to compete with inshore aquaculture only under limited circumstances, such as the following:

- When offshore weather and wave conditions are relatively mild, reducing the costs of building and operating offshore facilities relative to inshore aquaculture.
- When offshore farms enjoy significantly better water conditions than inshore farms, enabling faster growth or better survival.
- When offshore farms are able to supply market niches which cannot be supplied by inshore farms, for reasons such as lack of suitable sites, regulatory constraints and transportation costs.
- When offshore farms are able to take advantage of cost-lowering synergies with other facilities or activities such as existing inshore farm facilities or offshore oil rigs.

Over time, however, the economic potential for offshore aquaculture is likely to grow, for several reasons:

- Growing population and income will increase world demand for fish, raising prices.
- Technological change is likely to lower the relative cost of offshore aquaculture relative to inshore aquaculture. As in all industries (including inshore aquaculture) there will be a learning curve for offshore aquaculture. Over time, experience will help to identify ways to reduce costs. Economies of scale will help to bring down costs as the offshore industry expands and offshore operations expand in size.
- Growing population and income will increase relative values of competing uses of potential onshore and inshore farming areas, reducing the availability of those areas for inshore farming.

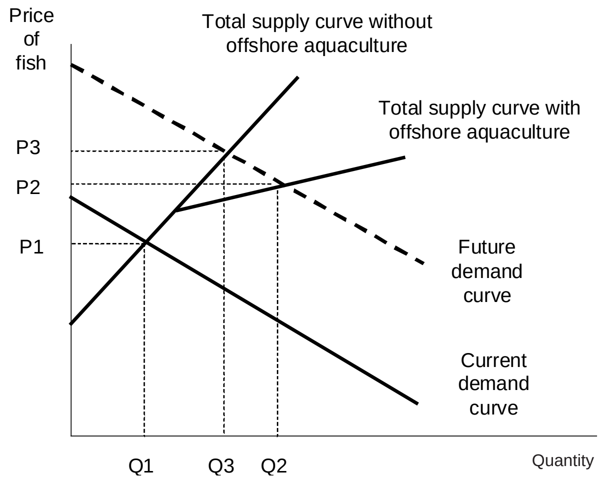
Among the most important factors affecting the economic potential for offshore aquaculture will be:

- The extent and pace of technological development in areas such as remote monitoring, remote feeding, and cage construction, and the extent to which these technological developments can reduce costs and risks of offshore farming.
- The extent to which offshore farms are able to achieve better growth rates and survival than inshore farms.
- The extent to which offshore facilities face fewer conflicts with other activities than inshore farms.
- The extent to which offshore farming is able to develop to a level at which it begins to realize significant economies of scale, and to spur the development of key supporting industries such as hatcheries, veterinary services, cage manufacture, and processing.
- The extent to which enabling regulatory frameworks establish clear, stable and timely processes for permitting and regulating offshore farms.

It is possible to envision a very wide variety of types of offshore aquaculture developing in the future. Many different species could potentially be farmed profitably offshore, in many different places, using many different kinds of technologies, for many different markets. There is no single answer about the economic potential for these many types of offshore aquaculture and when they might become profitable. The answers vary for different species, locations and technologies.

The world offshore aquaculture industry is still in its infancy. There has been only limited experience on which to judge its future potential. It is impossible to know with certainty what the long-run economic opportunities for offshore aquaculture may be. But it is reasonable to assume that they are real and substantial.

FIGURE 12
Effects of growth in fish demand



MARKET EFFECTS OF OFFSHORE AQUACULTURE

What are the potential effects of offshore aquaculture on world seafood markets? How will different groups and countries be affected? In previous sections, supply and demand analysis has been used to discuss factors that may drive the future growth of offshore aquaculture. Next supply and demand analysis can be used to examine potential market effects of offshore aquaculture.

Causes vs. effects of offshore aquaculture

It is important to distinguish between the *causes* and *effects* of offshore aquaculture. *Causes* are the changes in fish supply and demand curves which may make offshore aquaculture economically viable. *Effects* are the differences in prices and production that may occur with offshore aquaculture compared with those which would occur without offshore aquaculture.

For example, suppose the *cause* of offshore aquaculture is a growth in demand. As illustrated in Figure 12, the growth in demand from the current demand curve to a higher future demand curve causes the price to rise from P1 to P2 and causes total production to increase from Q1 to Q2. At the higher price level P2, part of total production is now from offshore aquaculture. Thus, the increase in demand caused an *increase in price* which made offshore aquaculture possible.

Suppose, however, that offshore aquaculture had not been an option. Without offshore aquaculture, the total supply curve would have been the steeper "total supply curve without offshore aquaculture." The increase in demand would have caused the price to rise even higher to P3, while causing production to rise only to Q3. Because the equilibrium price, P2, with offshore aquaculture is lower than the equilibrium price, P3, without offshore aquaculture, the *effect* of offshore aquaculture is to lower the price compared to what it would have been without offshore aquaculture.

In summary, then, the *cause* of offshore aquaculture might be an increase in demand resulting in higher fish prices, but the *effect* might be to keep fish prices from rising as much as they would without offshore aquaculture. Put differently, the *effects* of offshore aquaculture will be how future prices and production vary from what they would be without offshore aquaculture – not how they vary from today's prices and production.

Similarity of market effects for offshore and inshore aquaculture

What will distinguish offshore aquaculture from other types of marine aquaculture – at least in the near term – are the environments in which it takes place, the technologies needed to operate in those environments, and (potentially) the leasing and regulatory framework needed to operate. In contrast, initially there are not likely to be significant differences between offshore and inshore aquaculture in the species of fish which are grown, the products made from them, and where they are sold.

In some situations, offshore aquaculture may enjoy certain market advantages relative to inshore aquaculture. For example, offshore aquaculture might benefit from larger scales of production, closer location to major markets, or better environmental conditions potentially allowing fish to be grown to different sizes or to attain better quality. These conditions may in some cases be what make offshore aquaculture competitive.

In general, however, the market effects and issues for offshore aquaculture are generally likely to remain similar to those for inshore farming of the same species, as offshore farming grows to account for a larger share of production. Put differently, the market effects of offshore aquaculture will in general be similar to the market effects of any expansion of aquaculture production. These include effects on prices received by inshore farmers and fishers (and correspondingly on prices paid by consumers), and longer-term expansion of market demand potentially benefiting all producers.

FIGURE 13
Changes in consumer and producer surplus with additional sources of supply

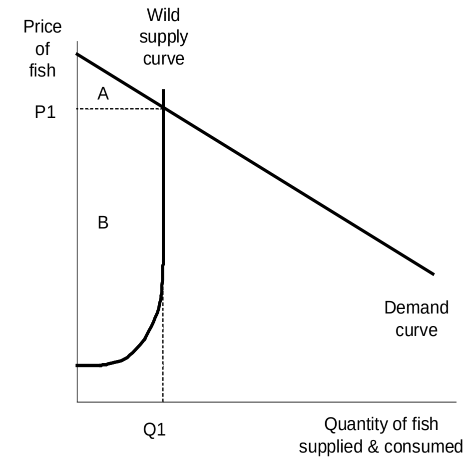


Figure 13A: Supply is only from wild fish

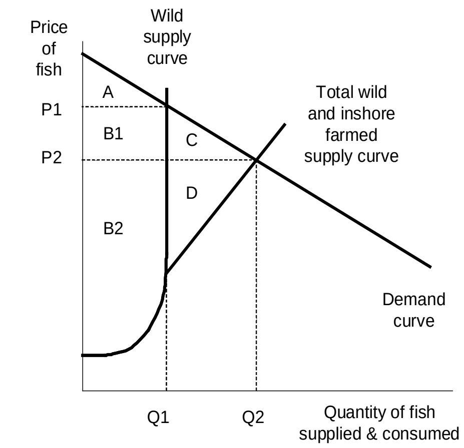


Figure 13B: Supply is from both wild fish and inshore aquaculture

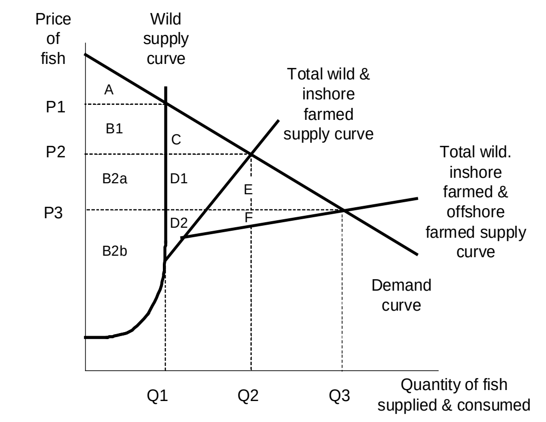


Figure 13C: Supply is from wild fish, inshore aquaculture, and offshore aquaculture

Potential market effects of growth in aquaculture supply on consumer and producer surplus

We may illustrate how different groups might be affected by additional supply from inshore and offshore aquaculture, and the net effects on society, as changes in what economists refer to as "consumer surplus" and "producer surplus". For simplicity, it is assumed initially that there is no change in demand for fish as supply increases (we relax this assumption later in our discussion).

Suppose that initially all fish supply is from a wild fishery. The supply curve for fish shows the total volume of fish offered for sale at any given price (Figure 13a). It is assumed that the supply curve is initially upward sloping, and becomes vertical at the maximum annual quantity available from the wild fishery. It is assumed total wild catches are limited by regulation rather than by fishing effort (which could potentially cause higher prices to result in lower catches over time).

The intersection of the wild supply curve with the demand curve determines the equilibrium price P1 and the equilibrium quantity sold Q1. At this price, the area of the graph labelled A shows what economists refer to as "consumer surplus": the difference between what consumers would have been willing to pay for fish (as shown by the demand curve) minus the price P1 that they actually pay. Similarly, the area of the graph labelled B shows what economists refer to as "producer surplus": the difference between the revenue received by wild fish producers and the revenue for which they would have been willing to supply the fish.

Consumer surplus is a measure of net benefits to consumers from the fishery. Producer surplus is a measure of net benefits to fishers from the fishery. The total net benefits to society from the fishery – the difference between what consumers would have been willing to pay and what it costs to produce the fish – are represented by the area A + B.

Now suppose that inshore aquaculture provides a new source of fish supply in addition to wild fish. For simplicity it is assumed initially that the farmed fish and wild fish are perceived in the market as identical species of identical quality. The effect of the development of inshore aquaculture is to shift the supply curve to the right, to the new "total wild and inshore farmed supply curve" (Figure 13b). This new total supply curve is the horizontal sum of the wild supply curve and an upward sloping inshore farmed supply curve (which is not shown in the graph).

As supply shifts from the old "wild supply curve" to the new "total wild and inshore farmed supply curve," the equilibrium price falls from P1 to P2, and the equilibrium quantity supplied and consumed increases from Q1 to Q2. Note that because the wild supply curve is depicted as vertical over this part of its range, there is no effect on the volume of wild fish supplied.

At the new equilibrium, consumer surplus is now represented by the sum of areas A, B1 and C, while producer surplus is now represented by the sum of areas B2 and D.

How are different groups affected by the introduction of inshore aquaculture (assuming there is no change in demand)?

- <u>Wild fishers are harmed because their prices fall.</u> Their producer surplus declines from area B to only area B2, or by an amount represented by area B1.
- <u>Inshore fish farmers benefit from the opportunity to earn profits.</u> They earn producer surplus represented by area D.
- <u>Consumers benefit because their prices fall.</u> Their consumer surplus increases from area A to areas A + B1 + C.

Total benefits to society increase from areas A + B to areas A + B1 + B2 + C + D. Areas C + D represent an increase in net benefits to society from inshore aquaculture, which are respectively the consumer surplus and producer surplus from inshore aquaculture. However, there is a redistribution of the benefits of the wild fishery from fishers to consumers by an amount represented by area B1. Put simply, in the short run, if inshore aquaculture depresses the price of wild fish, wild fishers lose and consumers gain by an equivalent total amount.

Note that the relative scale of these effects on fishers, consumers and fish farmers depend upon the assumptions we make about the shape of the supply and demand curves. In particular, if demand is highly "inelastic" (the demand curve slopes steeply downward, so that changes in supply cause big changes in price), the market effects of inshore aquaculture will be much greater than if demand is highly "elastic" (the demand curve is relatively flat, so that changes in supply cause only small changes in price).

Because there are far fewer fishers than consumers, the effects upon individual fishers are far greater than the effects on individual consumers. As the price falls, an individual fisherman may see a very large drop in his income. An individual consumer will experience a correspondingly large drop in the price of the fish she buys, but this will not be anywhere as significant for her overall welfare as the loss of income is for the fisherman.

Now suppose that offshore aquaculture provides yet another new source of fish supply in addition to wild fish and inshore aquaculture. Again, for simplicity we assume that all fish are perceived in the market as identical species of identical quality. The effect of the development of offshore aquaculture is to shift the supply curve still further to the right, to the new "total wild inshore farmed and offshore farmed supply curve" (Figure 13c). This new total supply curve is the horizontal sum of the wild supply curve and upward sloping inshore farmed supply and offshore farmed supply curves (which are not shown in the graph).

As the total supply curve shifts still further outwards, the equilibrium price falls from P2 to P3, and the total equilibrium quantity supplied and consumed increases from Q2 to Q3. At the new lower price, the volume of fish produced from inshore aquaculture is lower, but is more than made up for by the volume of fish produced from offshore aquaculture.

At the new equilibrium, consumer surplus is now represented by the sum of areas A, B1, B2a, C, D1 and E, while producer surplus is now represented by the sum of areas B2b, D2 and F.

How are different groups affected by the introduction of offshore aquaculture in the short run (assuming there is no change in demand)?

- <u>Wild fishers are harmed because their prices fall</u>. Their producer surplus declines from area B2 to only area B2b, or by an amount represented by area B2a.
- <u>Inshore fish farmers are harmed because their prices fall</u>. Their producer surplus declines from area D to only area D2.
- <u>Offshore fish farmers benefit from the opportunity to earn profits</u>. They earn producer surplus represented by area F.
- <u>Consumers benefit because their prices fall</u>. Their consumer surplus increases from area A + B1 + C to area A + B1 + C + B2a + D1 + E.

Total benefits to society increase from areas A + B + C + D to areas A + B + C + D + E + F. Areas E + F represent an increase in net benefits to society from offshore aquaculture, which are respectively the consumer surplus and producer surplus from offshore aquaculture. However, there is again a redistribution of the benefits from wild fishers and inshore aquaculture producers to consumers by an amount represented by area B2a + D1. Put simply, to the extent that offshore farming lower fish prices, fishers and inshore fish farmers stand to lose but consumers stand to gain.

Again, note that the relative scale of these effects on fishers, consumers and fish farmers depend upon the assumptions made about the shape of the supply and demand curves. In particular, if demand is inelastic (the demand curve slopes down steeply), offshore aquaculture may have big effects on prices; while if demand is elastic (the demand curve is relatively flat), offshore aquaculture may have only small effects on prices.

Again, because there are far fewer fishers and inshore farmers than consumers, the effects upon individual fishers and inshore farmers are far greater than the effects on individual consumers.

Relative effects of offshore aquaculture on different countries

The preceding analysis considered the potential market effects of offshore aquaculture on fishers, inshore and offshore fish farmers and consumers without regard to the question of where they live. In general, fishers and inshore fish farmers stand to lose from offshore aquaculture (because their prices fall), while offshore fish farmers stand to gain (from the opportunity to earn profits) and consumers stand to gain (because fish prices fall).

Given the fact that fish are traded widely, the effects of offshore aquaculture of a particular species may vary widely between countries depending on the relative extent to which their populations include fishers who catch the species, inshore farmers who grow the species, offshore farmers who would grow the species and consumers who eat the species.

Table 2 shows sixteen potential "scenarios" for combinations of these different groups which might live in a country. A country will clearly gain from offshore aquaculture of a species if it has no fishers or inshore farmers who produce that species, but it has offshore farmers of and/or consumers of that species (Scenarios 2, 3 and 4). Similarly, a country will clearly lose from offshore aquaculture if it has no offshore farmers or consumers of the species, but it has fishers and inshore farmers of the species

TABLE 2
Change in net benefits to a country from domestic or foreign offshore farming of a species

Scenario	Groups which are included in the population of the country				How groups are affected by domestic or foreign offshore farming of the species				Change in net benefits to the country from domestic or foreign offshore farming of the species
	Fishers who catch the species in capture fisheries	Inshore farmers of the species	Offshore farmers of the species	Consumers of the species	Fishers	Inshore farmers	Offshore farmers	Consumers	
1									No effect
2				X				Gain	Gain
3			X				Gain		Gain
4			X	X			Gain	Gain	Gain
5		X				Lose			Lose
6		X		X		Lose		Gain	Uncertain*
7		X	X			Lose	Gain		Uncertain
8		X	X	X		Lose	Gain	Gain	Uncertain*
9	X				Lose				Lose
10	X			X	Lose			Gain	Uncertain*
11	X		X		Lose		Gain		Uncertain
12	X		X	X	Lose		Gain	Gain	Uncertain*
13	X	X			Lose	Lose			Lose
14	X	X		X	Lose	Lose	Gain	Gain	Uncertain*
15	X	X	X		Lose	Lose	Gain		Uncertain
16	X	X	X	X	Lose	Lose	Gain	Gain	Uncertain*

* Scenarios in which consumers stand to benefit from lower prices and expanded supply, but fishers and/or inshore farmers stand to lose from lower prices.

(Scenarios 5, 9 and 13). For other scenarios, the change in net benefits to the country is uncertain: it depends on the relative scale of and effects on groups which stand to lose and groups which stand to gain.

More generally, as with inshore aquaculture, different offshore producing countries and firms will compete with each other in international markets. The countries where investment first occurs may enjoy competitive advantages deriving from economies of scale in farming, juvenile production, processing, distribution and many other land-based support activities. However, over time they may face competition from new lower-cost producing companies taking advantage of established technologies. As has occurred with inshore aquaculture, this may lead to financial difficulties for higher-cost producing countries, trade disputes, and direct and indirect trade barriers.

Potential market effects of growth in aquaculture supply on consumer and producer surplus with growing demand

The preceding analysis assumed that the demand for fish was unchanged by the introduction of aquaculture. However, over time introducing new supply from inshore and offshore aquaculture is likely to increase demand for fish, shifting the demand curve out.

There are several reasons for which new supply from aquaculture is likely to increase fish demand over time. First, at any given time, demand for fish reflects consumers' tastes and preferences, which in turn reflect their past consumption experiences. If a particular fish species is expensive, consumers who have not eaten it in the past are less likely to buy it in a store or order it in a restaurant. As the price falls, consumption increases, as illustrated by the increase in consumption from Q1 to Q2 in Figure 13b and from Q2 to Q3 in Figure 13c. Part of the increase in consumption is because new consumers try the fish. As these new consumers become familiar with and develop a taste for the fish, over time they may be willing to pay a higher price for it than they would have previously.

Second, consumer demand for fish is limited by its availability in stores and restaurants. Even if consumers like a fish and are willing to pay a high price for it, they will not buy it if it is not in their local stores or on their local menus. As aquaculture supply expands, fish are offered for sale in more geographic locations, in more kinds of stores and restaurants and at more times of the year, thus increasing the total demand at any given price.

Third, fish farmers engage in marketing in a systematic effort to increase demand. They recognize that their economic success depends critically on expanding the market for their products. Marketing by fish farmers is not just advertising to consumers. Rather, it is a systematic approach to understanding and responding to the needs of both consumers and store and restaurant buyers, reflected in (for example) product forms, quality standards, packaging, timing and volume of fish deliveries, long-term contracts, supply guarantees, payment terms, etc. (Note that without competition from aquaculture, wild fishers have less incentive to engage in marketing, particularly when prices are high, because they are limited by nature in the volume of fish that they can supply and cannot expand their total production).

Figure 14 illustrates potential longer-run effects of an increase in fish demand as aquaculture grows. With expanded demand, the price increases back from P3 to P4 and the quantity of fish supplied and consumed increases from Q3 to Q4.

The increase in demand benefits all producer groups:

- Fishers producer surplus increases by an amount represented by area I.
- Inshore fish farmer's producer surplus increases by an amount represented by area J.
- Offshore fish farmers' producer surplus increases by an amount represented by areas K + L.

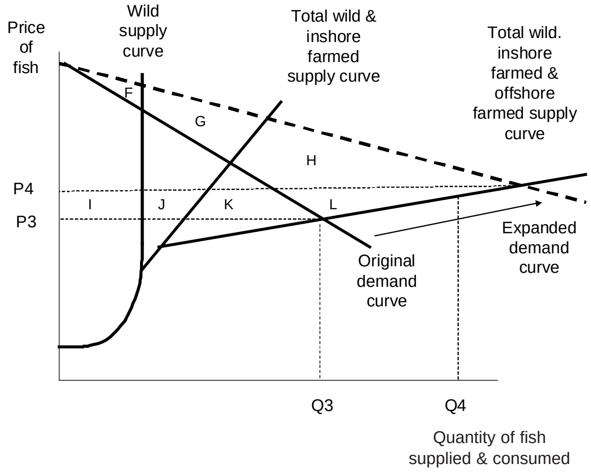
Some consumers lose from the increase in demand but others benefit. As the price rises from P3 to P4:

- Those consumers whose demand was represented by the original demand curve and who had previously been purchasing fish for the lower price P3 experience a loss of consumer surplus represented by areas I + J + K.
- New consumers (as well as former consumers who enjoy fish more) experience an increase in consumer surplus represented by areas F + G + L.

The increase in demand increases total benefits to society by an amount represented by areas F + G + H + L. Higher demand also reduces the extent to which aquaculture results in a shift of net benefits from fishers to consumers.

Thus, over the long-term, if growth in aquaculture supply (from offshore aquaculture or any other kind of aquaculture) is accompanied by growth in demand, there will be smaller effects on previous wild and farmed producers. If the increase in demand is sufficiently high there may be no long-term effect on the price and existing producers may not be harmed at all – or could even be helped.

FIGURE 14
Potential longer-run effects of increase in fish demand due to aquaculture



Potential market differentiation of offshore fish

The preceding discussion assumed that consumers view all fish of a given species as identical – so that changes in supply from any given source (such as offshore farming) can affect prices for producers from other sources (such as wild fisheries).

However, another potential change in demand which may arise over time as a result of aquaculture – including offshore aquaculture – may be a differentiation in consumer demand for different sources of supply, such as between wild and farmed fish or between fish farmed inshore and fish farmed offshore.

As total world production of fish expands and more consumers in more places eat more fish in more product forms, both buyers (e.g. retailers and food service operators) and consumers may come to perceive differences between fish of the same species produced in different ways, resulting in price premiums for some fish from some origins and price discounts for others. For example, following the emergence of large-scale salmon farming, some (not all) consumers came to perceive some (not all) species of wild salmon as superior to farmed salmon, thus, tending to offset in part the effects of increased farmed salmon supply on wild salmon prices.

It is possible (although far from certain) that similar market differentiation could emerge over time for fish grown in offshore farms. For example, if fish grown in offshore farms came to be perceived as "cleaner" or more "environmentally responsible" this could increase demand for offshore-grown fish relative to inshore-grown fish, increasing the market impacts on inshore-grown fish.

The importance of marketing

As with inshore aquaculture, marketing will be critical for the future of offshore aquaculture – for individual firms engaged in offshore aquaculture, for countries with offshore aquaculture, for species grown on offshore farms – and more broadly for all fish producers.

Without marketing to ensure growth in demand, increases in aquaculture production – inshore of offshore – will tend to lower prices, eventually to levels at which expanded (or even existing) production levels are no longer profitable. Only by continuing to expand demand can production continue to rise. For example, the vast growth in salmon production over the past three decades has been possible only because salmon farmers have greatly expanded demand: salmon is now consumed in far more countries, by far more people, in far more product forms.

Note that effective marketing will be particularly important for "new" species which may be found to be suitable for offshore farming but which are not farmed in significant volumes onshore. The greater the share of total production of a species that offshore aquaculture represents, the greater the potential for incremental offshore production to have significant market effects.

Summary: market effects of offshore aquaculture

In the short run, growth in offshore aquaculture production will tend to lower fish prices by increasing the supply of fish, harming fishers and inshore farmers but benefiting consumers. The extent to which different countries benefit from or are harmed by offshore aquaculture will depend on the extent to which their citizens are consumers of fish grown offshore, producers of fish grown offshore, or producers of fish which compete with fish grown offshore.

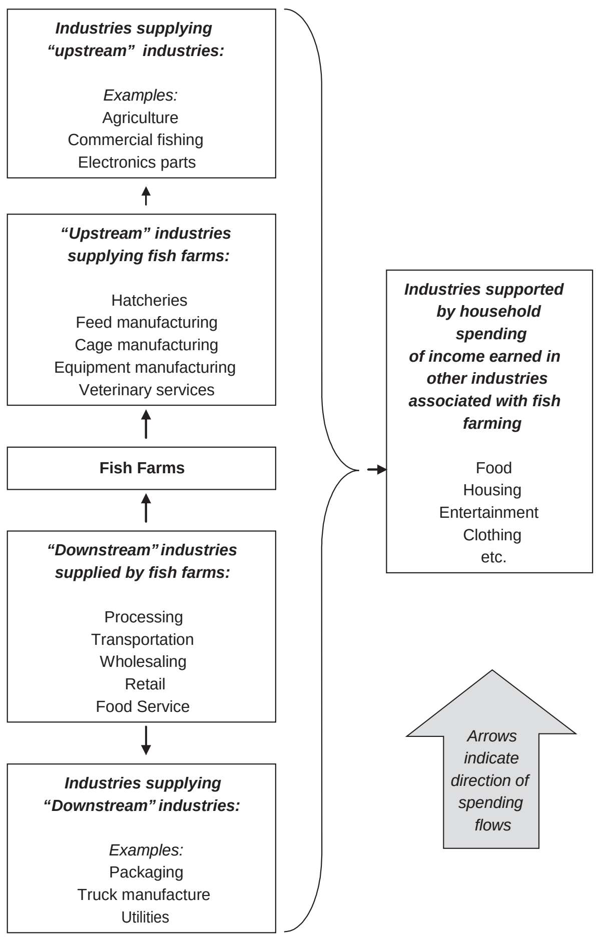
Over the longer run, however, growth in offshore aquaculture production will tend to increase the world demand for fish as consumers become more familiar with fish; as fish become available in more locations, at more times, and in more product forms; and as offshore fish farmers engage in systematic marketing to expand demand. Increasing demand will tend to offset the effects of increasing supply on prices.

ECONOMIC IMPACTS OF OFFSHORE AQUACULTURE

What will the economic impacts of offshore aquaculture be? How many people will offshore aquaculture employ, in what kinds of jobs, and earnings what kind of incomes?

The starting point in answering these questions is to recognize that fish farming, regardless of where or how it is done, creates jobs and income in many more places and industries than on fish farms per se. Figure 15 provides a simple categorization of industries which depend in some way on fish farming. We may group these industries into six categories:

FIGURE 15
Industries associated with fish farming



- Fish farms. These are aquaculture operations growing fish or shellfish.
- "Upstream industries" supplying fish farms. These are industries from which the fish farms purchase direct inputs. Among the industries which account for the greatest share of fish farm purchases are hatcheries, feed manufacturing and cage and equipment manufacturing.
- "Downstream" industries supplied by fish farms. These are industries in the distribution chain from fish farms to consumers, including processing, transportation, wholesaling, retail and food service.
- Industries supplying upstream industries. These are industries from which the "upstream" industries purchase inputs. For example, the feed manufacturing industry purchases raw material for making fish feed from both the agriculture and the commercial fishing industries.
- Industries supplying downstream industries. These are industries from which the "downstream industries purchase inputs. For example, the processing industry purchases boxes from the packaging industry.
- Industries supported by household spending. These are industries throughout the entire economy that are supported by spending of household income earned in the other industries.

Clearly the nature and degree of association with fish farming varies widely among these different categories of industries. There are only a few industries which would disappear entirely without fish farming, such as farm cage manufacturing. However, there are many industries, across many sectors of the economy – which benefit in some way from fish farming.

Figure 15 helps to illustrate two simple, but important points. First, the economic impacts of fish farming are larger – potentially much larger – than those which occur at fish farms. The employment created by aquaculture cannot be counted simply by adding up the jobs at aquaculture companies.

Second, the economic impacts of fish farming are spread over a far greater geographic area than the communities where fish farms are located or from which they are supported. While the hatchery supplying a fish farm may be located relatively near the farm, the company manufacturing the cage or the restaurant selling the fish may be located thousands of miles away.

One indicator of the relative significance of "upstream industries" in aquaculture production is the share of purchased product inputs in the gross output value of aquaculture. As shown in Table 3, purchased inputs accounted for 69 percent of total gross output value of Canadian aquaculture in 2005, and feed purchases alone accounted for 31 percent. The shares of different inputs varied between provinces, reflecting different mixes of species in total production.

Viewed in a different way, gross value added in Canadian aquaculture was only 31 percent of gross output in 2005. Thus, more than two-thirds of gross output value was generated in other "upstream" industries.

Adding up how many people work on actual fish farms and what they earn is a relatively straightforward process. Speculating about how many people might work on future offshore fish farms is also relatively straightforward (although highly uncertain given uncertainty about the future scale and characteristics of the industry). However, it is far less straightforward to measure the full economic impacts, across all industries, of existing fish farms – or to project the potential full economic impacts of future fish farms.

One approach for estimating economic impacts of an industry is input-output analysis, which calculates economic impacts using assumptions about inter-industry purchases per dollar of output of an industry. These may then be used to calculate three types of economic impacts: "direct," "indirect," and "induced." Applied to fish farming, "direct impacts" are those occurring within the fish farming industry; "indirect" impacts are those driven by purchases of the fish farming industry from other industries and "induced impacts" are those driven by household spending of income created by direct and indirect impacts. Each of these types of impacts is typically measured in three ways: annual average employment, wage and salary income and sales or "output."

Input-output analysis typically measures only the impacts of an industry and its associated upstream activities. If one wishes to measure the impacts of the "downstream" activities of processing and distributing farmed fish, the same approach may be applied to estimating the direct, indirect and induced impacts of these industries (net of those associated with fish production).

TABLE 3
Estimated share of selected expenditures in gross output value of Canadian aquaculture, 2005

	Newfound-land (%)	Prince Edward Island (%)	Nova Scotia (%)	New Brunswick (%)	Quebec (%)	Ontario (%)	British Columbia (%)	Canada total (%)
Purchased product inputs	**59**	**24**	**47**	**75**	**40**	**43**	**74**	**69**
Feed	28	–	24	29	–	24	38	31
Eggs and fish for growout	7	8	7	10	2	5	3	6
Processing services	4	2	0	4	0	–	10	6
Goods transportation/storage	4	1	2	2	1	1	7	4
Energy	2	2	2	1	8	3	2	2
Maintenance/repairs	2	3	1	–	3	1	3	3
Insurance premiums	–	0	1	2	1	0	2	2
Rental/leasing expenseses	1	2	0	1	1	1	1	1
Professional services	2	1	1	1	2	1	1	1
Therapeutants	–	–	2	1	–	–	2	2
Gross value added (factor cost)	**33**	**76**	**53**	**25**	**59**	**57**	**27**	**31**
Salaries/wages	11	37	17	12	19	17	11	13
Finfish share of production volume	61	0	64	94	25	100	87	75

Source: Calculated from value-added account data in Statistics Canada, Aquaculture Statistics 2005, Catalogue No. 23-222-XIE. Estimates were based on taxation data and a sample of 148 establishments. Blank cells indicate estimates were not available.

A significant challenge for input-output analysis is that it requires extensive data on inter-industry purchases. This is particularly a challenge for marine aquaculture, partly because it relies heavily on purchases from other industries and partly because it is a relatively new industry for which relatively few data are available.

Kirkley (2008) developed an input-output model for the purpose of estimating potential economic impacts of the United States of America's offshore aquaculture. For each species, the model required specific assumptions about the scale of the operation and different kinds of expenditures such as farm installation costs, vessel maintenance, feed costs, etc. The model then calculated direct, indirect and induced impacts generated by the farming operation, as well as "downstream" activities.

Table 4 summarizes the relative shares of estimated direct, indirect and induced employment impacts of farming and downstream activities. The estimated direct employment impacts of fish farming accounted for between only 11 percent and 19 percent of the projected total employment impacts of farming from all upstream and downstream activities, as well as induced activity in the rest of the economy. As shown in the fourth row, the total impacts attributable to farming (as opposed to downstream activities) represented only 27 percent to 38 percent of total impacts.

Thus, the potential total employment and income impacts of offshore fish farming are much larger than those which would occur at the farming operations alone – potentially five to ten times larger. Put differently, simply adding up jobs and wages at the farms would greatly underestimate the total economic impacts created by offshore farming.

Note that as with the market impacts discussed earlier, the employment and income impacts of offshore aquaculture would not necessarily occur fully or even primarily within the countries where the offshore farms are located. For example, to the extent the feed or cages are manufactured in a different country, or the fish are transported to and sold in a different country, the economic impacts may occur in other countries. Put differently, in an increasingly globalized economy, economic activity anywhere may have indirect and induced economic effects in many other countries.

Table 5 shows Kirkley's projections of employment impacts per thousand metric tonnes of annual production for each species. The important point is not the specific impacts projected for any particular species (which depend on numerous assumptions about the scale and technology of each farming operation), but that there is wide variation between species in the scale of potential economic impacts associated with a given production volume. This is to be expected, given the fact that technologies of fish farming vary widely depending upon what species is being farmed and how it is being farmed.

TABLE 4
Share of estimated employment impacts of potential offshore aquaculture operations

	Blue mussel (%)	Sea scallop (%)	Cod (%)	Atlantic salmon (%)	Winter flounder (%)
Farming direct	11	11	15	14	19
Farming indirect	4	1	10	6	7
Farming induced	13	16	12	16	12
Farming total	**27**	**29**	**36**	**35**	**38**
Downstream direct	43	3	38	38	37
Downstream indirect	3	2	2	2	2
Downstream induced	26	26	24	24	23
Downstream total	**73**	**71**	**64**	**65**	**62**
Combined direct	53	54	52	52	56
Combined indirect	7	4	12	8	9
Combined induced	39	42	35	40	35
Combined total	**100**	**100**	**100**	**100**	**100**

Source: Full-time and part-time employment impacts estimated for different types of United States of America offshore aquaculture operations by Kirkley (2008).

TABLE 5
Estimated employment per thousand metric tonnes of annual production in potential United States of America offshore aquaculture operations

	Blue mussel	Sea scallop	Cod	Atlantic salmon	Winter flounder
Farming direct	11	155	70	36	146
Farming indirect	4	18	47	15	53
Farming induced	13	218	56	43	91
Farming total	**29**	**391**	**173**	**93**	**290**
Downstream direct	45	588	180	101	284
Downstream indirect	3	32	12	6	18
Downstream induced	28	360	113	63	178
Downstream total	**76**	**980**	**305**	**170**	**480**
Combined direct	56	743	250	136	430
Combined indirect	7	50	58	21	71
Combined induced	41	578	169	106	268
Combined total	**104**	**1370**	**477**	**263**	**770**

Source: Full-time and part-time employment impacts estimated for different types of United States of America offshore aquaculture operations by Kirkley (2008).

Table 6 shows estimates of annual average employment in aquaculture per thousand metric tonnes of production, for various regions and species, from a number of different sources. The estimates are for inshore marine aquaculture and onshore aquaculture, which likely differ in their employment impacts from those of potential future U.S. offshore farms. The definitions of "employment" and the methodologies used to derive the estimates of employment vary considerably between sources.

TABLE 6
Selected estimates of aquaculture employment, various species and regions

Species	Region	Year	Source and notes*	Live weight (mt)	Estimated employment	Estimated employment per '000 tonnes
All aquaculture	Newfoundland	2005	1	8 163	200	25
	Prince Edward Island			18 921	620	33
	Nova Scotia			8 917	250	28
	New Brunswick			37 657	1 250	33
	Quebec			1 215	155	128
	Ontario			4 000	150	38
	British Columbia			73 195	1 275	17
	CANADA TOTAL			**152 068**	**3 900**	**26**
All aquaculture	Austria	1997	2	4 274	379	89
	Belgium			1 471	112	76
	Denmark			38 250	698	18
	Finland			16 365	809	49
	France			211 205	10 342	49
	Germany			59 069	3 193	54
	Greece			54 947	2 711	49
	Ireland			35 101	1 275	36
	Italy			211 919	4 923	23
	Netherlands			97 640	564	6
	Portugal			8 781	1 452	165
	Spain			233 693	7 851	34
	Sweden			6 523	480	74
	United Kingdom			128 525	2 705	21
	EU TOTAL			**1 107 763**	**54 029**	**49**
All aquaculture	Europe	1998	3	1 315 000	57 000	43
Salmon	N. Brunswick	2000	4	29 100	1 683	58
Salmon	Maine	2002	5	6 695	240	36
Salmon	Scotland	1997	6	99 197	1 647	17
Salmon	Scotland	2002	7	143 000	1 552	11

TABLE 6 (CONTINUED)

Species	Region	Year	Source and notes*	Live weight (mt)	Estimated employment	Estimated employment per '000 tonnes
Salmon & trout	Norway	2000	8	488 839	3 631	7
		2005		645 387	3 054	5
Species other than salmon & trout	Norway	2000	8	1 439	400	278
		2005		11 507	606	53
Catfish	Mississippi	2001	7	172 789	3 000	17

*Sources and notes are listed below.

General notes: To the extent possible, employment data are estimates of full-time-equivalent employment in fish farming (excluding upstream or downstream impacts, including processing). The kind of employment data collected and/or estimated varies between studies. See notes for individual sources for additional details.

1) Fisheries and Oceans Canada. 2006. Canadian Aquaculture Industry, 2004-2005: Key Figures. www.dfo-mpo.gc.ca/Aquaculture/ref/kf0405_e.htm
2) MacAlister Elliott and Partners, Ltd. 1999. Forward Study of Community Aquaculture: Summary Report. Prepared for European Commission Fisheries Directorate General. Note: Species mix varies widely between EU countries. Employment estimates are for full-time-employment in production.
3) Commission of the European Communities. 2002. A Strategy for the Sustainable Development of European Aquaculture. Brussels 19.9.2002, COM(2002) 511 final. Note: Reported production volume is for 2000. Estimated 1998 employment was "at least 80 000 full or part-time workers, equivalent to 57 000 full-time jobs" (see page 4).
4) Stewart, Len (Aquaculture Strategies, Inc.) 2001. Salmon Aquaculture in New Brunswick: Natural Development of Our Marine Heritage. Prepared for New Brunswick Salmon Growers Association Aquaculture Strategies. Note: Estimated person-years employment includes 157 in hatcheries, 624 in growout, 537 in processing, 240 in direct services, and 125 in "selling, administration and other." 77.3 percent of jobs were full-time, 9.6 percent were part-time, and 13.1 percent were seasonal.
5) O'Hara, Frank, Charles Lawton and Matthew York (Planning Decisions, Inc.). 2003. Economic Impact of Aquaculture in Maine. Prepared for the Maine Aquaculture Innovation Center. Note: Includes employment at three companies producing 6 800 tonnes of salmon annually of "over 240 full-time workers" in "freshwater and ocean farming operations, processing plants, and administrative and sales positions."
6) Highlands and Islands Enterprise and The Scottish Office. 1998. The Economic Impact of Salmon Farming, Final Report. Prepared by Public and Corporate Economic Consultants (PACEC) and Stirling Aquaculture. 124 pp. Employment is estimated FTE employment in smolt production and salmon production. The study estimated that additional FTE employment of 4 777 is created in "processing, supplier and induced."
7) Scottish Executive, 2004. Scottish Economic Report: March 2004. Scottish Salmon Farming. www.scotland.gov.uk/library5/finance/ser04-16.asp. Note: Estimates are for FTE employment of 1 552 in smolt and salmon farming. Additional FTE employment of 4 728 for salmon farming, 1 024 for farming suppliers, and 520 for processing suppliers.
8) Statistics Norway. 2007. Fish Farming 2005. www.ssb.no/nos_fiskeoppdrett. *Note:* Includes employment in hatcheries.
9) Hanson, Terrill, Stuart Dean, and Stan Spurlock. Economic Impact of the Farm-Raised Catfish Industry on the Mississippi State Economy. Department of Agricultural Economics, Mississippi State University. Note: Includes only employment in catfish production. Additional employment of 3 671 was reported in catfish processing. Production of 172 789 tonnes is volume of catfish processed in Mississippi, USA.

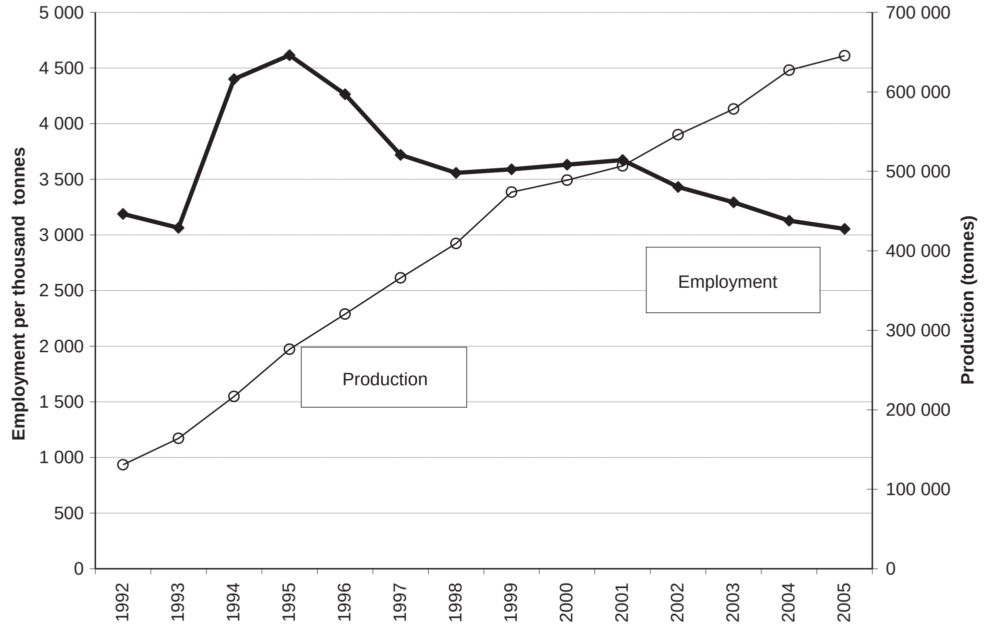
The employment estimates are only for direct employment in fish farming. As discussed above, total employment created by aquaculture in these regions, after accounting for indirect and induced upstream impacts of upstream and downstream activities, is likely much larger – potentially five to ten times as great.

The employment impacts associated with a given volume of aquaculture production vary widely depending upon the species, region and technology and scale of production. In general, labour productivity is much higher in large-scale salmon farming, resulting in the creation of fewer direct farming jobs per thousand metric tonnes of production than smaller-scale farming of other species.

Norwegian salmon and trout farming – probably the most labour-efficient large-scale aquaculture in the world – creates about 5 direct farming jobs per thousand tonnes of production. In contrast, aquaculture in general, reflecting smaller-scale production of a mix of finfish and shellfish species, tends to create between 20 and 50 direct farming jobs per thousand tonnes of production.

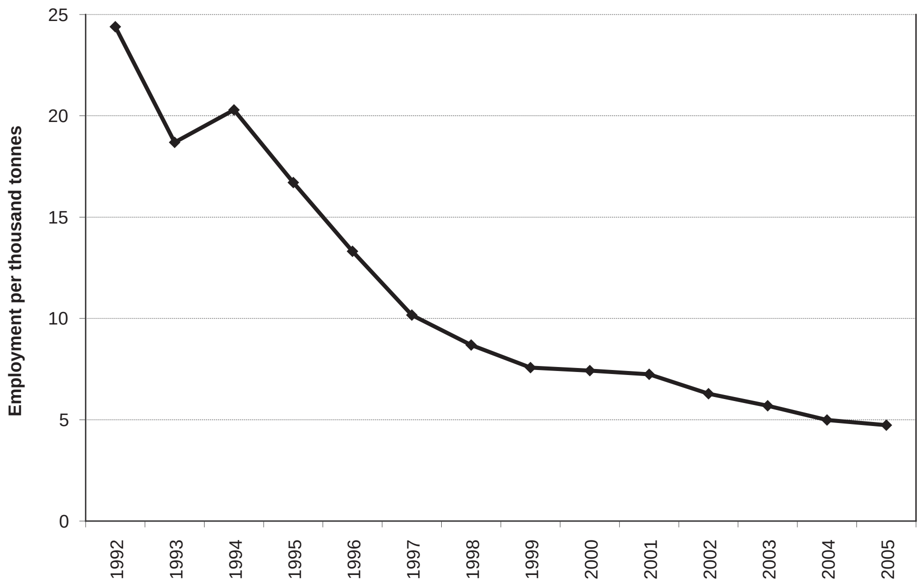
Detailed cost and employment data compiled annually for the Norwegian aquaculture industry help to illustrate the basic point that the number of jobs created by fish farming depend upon scale, technology and economics. Between 1992 and 2003, Norwegian salmon and trout production more than quadrupled while total employment in Norwegian salmon and trout farming declined (Figure 16a). As a result, employment per thousand metric tonnes of salmon and trout production fell from 24.4 to 5.7 (Figure 16b) – reflecting a dramatic increase in labour productivity as the scale of the industry increased.

FIGURE 16A
Norwegian salmon and trout aquaculture: total production and total employment



Calculated from data in Statistics Norway, *Fish Farming 2005*.

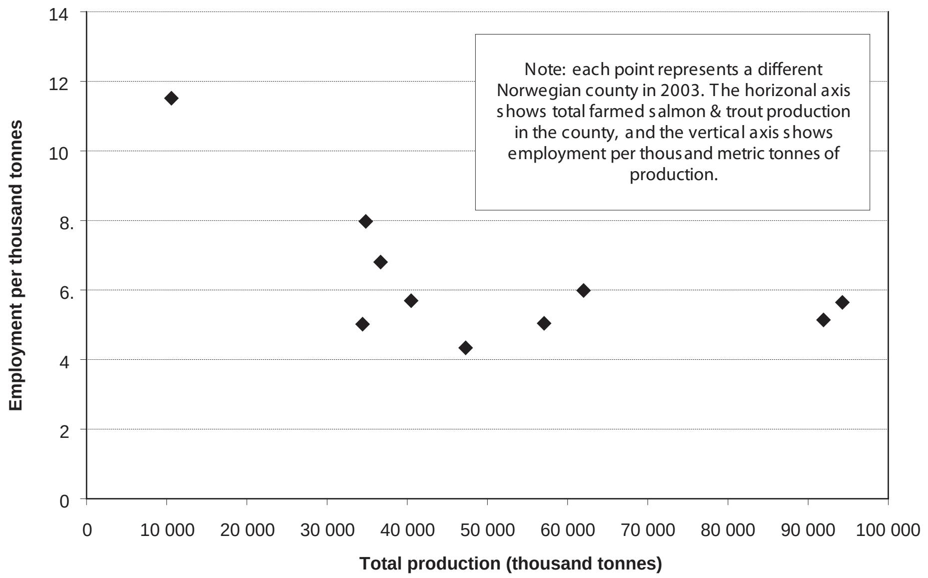
FIGURE 16B
Norwegian salmon and trout aquaculture: total production and total employment



Calculated from data in Statistics Norway, *Fish Farming 2005*.

Norwegian aquaculture data also help to illustrate that even farming of the same species in the same country may have different job impacts in different locations – likely reflecting differences in industry scale. As shown in Figure 17, there were significant differences between Norwegian counties in the employment per thousand metric tonnes of production in 2003.

FIGURE 17
Norwegian salmon and trout aquaculture: total production and total employment



Calculated from data in Statistics Norway, *Fish Farming 2005*.

In general, because of the more difficult working conditions offshore and the higher cost of transporting workers to offshore facilities, offshore fish farms are likely to be more mechanized and have fewer people working on the farm sites per tonne of production than inshore farms growing the same species. Put differently, where it is possible to replace offshore workers with machines, offshore farm operators are likely to try to do so. This effect will be amplified to the extent that offshore farms are larger scale than inshore farms.

However, some parts of offshore fish farming operations may employ more labour than inshore operations producing comparable species and volumes. For example, because of generally longer distances from shore facilities to farms, offshore farms may create relatively more jobs in transporting fish, feed, equipment and people to and from farms.[5]

Clearly the employment in offshore aquaculture will depend upon the volume of offshore aquaculture production, the mix of species which are farmed and the scale and technology of individual farming operations. However, given observed levels of employment in existing capital-intensive inshore aquaculture, is possible to make reasonable estimates about the potential scale of total employment which might be created by any given level of offshore production.

Table 7 shows the potential total employment implied by different combinations of three assumptions:

- Total annual production. The table shows implications of annual production from 50 000 to 500 000 tonnes.
- Direct farming employment per thousand tonnes. The table shows implications of direct employment ranging from five jobs per thousand tonnes (large-scale highly efficient Norwegian salmon and trout farming) to 50 jobs per thousand tonnes (averages across all aquaculture in some regions).

[5] Note that locating a farm farther offshore does not necessarily imply a greater transportation distance from shore facilities. Depending on terrain and infrastructure development, the distance from a shore facility straight out to an offshore farm may be shorter than the distance along the coast to a suitable inshore farming site.

- Ratio of total employment to direct farming employment. The table shows implications of between two and ten total jobs per direct farming jobs. Note that the lower assumption would exclude "downstream" employment created in transportation, wholesaling, retail and food service.

TABLE 7
Potential employment created by offshore aquaculture implied by different combinations of assumptions

	Assumed direct farming employment per thousand tonnes	Assumed annual offshore production (tonnes)		
		50 000	100 000	500 000
Direct farming employment only	5	250	500	2 500
	20	1 000	2 000	10 000
	50	2 500	5 000	25 000
Assuming 2 total jobs per direct farming job	5	500	**1 000**	**5 000**
	20	**2 000**	**4 000**	**20 000**
	50	**5 000**	10 000	50 000
Assuming 5 total jobs per direct farming job	5	1 250	**2 500**	**12 500**
	20	**5 000**	**10 000**	**50 000**
	50	**12 500**	25 000	125 000
Assuming 10 total jobs per direct farming job	5	2 500	5 000	25 000
	20	**10 000**	20 000	100 000
	50	**25 000**	50 000	250 000

Note: Relatively more likely combinations of assumptions are shown in **bold**.

On average, the jobs created in offshore aquaculture are likely to be higher-skilled and higher-paying than the jobs in onshore and inshore aquaculture for similar species. These jobs will include, for example, operation and maintenance of vessels and remote monitoring and feeding facilities and fish nutrition and fish health specialists.

As with other higher-skilled and higher paying jobs, not all of the new jobs created by offshore aquaculture will necessarily be taken by current residents of those communities nearest offshore aquaculture facilities. The industry is likely to seek the most qualified employees it can find from a broader regional or national pool of workers with the requisite skills. However, local communities may be able to influence local hiring through training programmes or tax incentives. Local training or hiring requirements could potentially be incorporated in enabling regulations for offshore aquaculture.

Commercial fishers would be well skilled for and could potentially work in many of the jobs that might be created by offshore aquaculture, particularly those that involve vessel operations, maintenance of offshore operations and transportation of fish. However, some (but not all) kinds of offshore aquaculture – particularly large-scale corporate farms – may involve a very different working environment than commercial fishing. Some but not all fishers and other coastal community residents would welcome these job opportunities.

In considering the types of jobs created by offshore aquaculture, it is important to keep in mind the point emphasized earlier in this chapter that most of these jobs will not be working on offshore farms or working for offshore aquaculture companies. Rather, most of the jobs will be in a wide variety of upstream and downstream activities such as hatcheries, feed manufacturing, soybean farming (for feed ingredients), cage manufacturing, software development (for remote monitoring systems) and fish processing and distribution.

ECONOMIC IMPLICATIONS OF GOVERNMENT POLICIES FOR OFFSHORE AQUACULTURE

In the previous section, how economic factors may affect offshore aquaculture development was examined – assuming that government policies provide an enabling regulatory framework for offshore aquaculture. In this section, we examine how

TABLE 8
Selected government policies affecting the offshore aquaculture development

Category	Selected key issues
Leasing policies	Is there a process by which farmers may lease offshore sites?
	How predictable is the process?
	How long does it take?
	How legally secure are sites?
	How flexible are permitted uses of sites?
	Can sites be transferred?
	What do sites cost?
Regulatory policies	What regulations does government impose on offshore farmers?
	How costly are the regulations?
	What is the process for developing regulations?
	How stable and predictable are the regulations?
	What are the objectives of the regulations?
	How efficient are the regulations? Could the same objectives be achieved at lower cost?
Other policies	How is offshore aquaculture taxed?
	What kinds of subsidies are available for the offshore aquaculture industry?
	To what extent and in what ways does government support offshore aquaculture research, education and marketing?
	What are trade policies towards farmed fish?
	What infrastructure (roads, ports, etc.) does government provide in areas with offshore aquaculture potential?

government policies may affect the offshore aquaculture development assuming that economic factors are favourable.

A wide variety of government policies may affect the development of offshore aquaculture. These policies may be grouped broadly as leasing policies, regulatory policies and other policies (Table 8).

Leasing and regulatory policies are critically important for offshore aquaculture. Offshore aquaculture cannot and will not happen unless governments establish leasing and regulatory policies which give fish farmers the opportunity and incentive to invest in offshore fish farming.

Just as importantly, without the potential for eventual economic benefit, companies will not invest in research on how to address potential engineering or other challenges for offshore aquaculture. Until actual offshore operations are in place, there is no opportunity to learn from experience about how to address the challenges. The surest way to ensure that no solutions are found for these challenges is to ban offshore aquaculture until they are found. The surest way to ensure that no benefits are realized from offshore aquaculture is to ban offshore aquaculture until the benefits are proven.

Having an enabling regulatory policy does not in any way imply that offshore aquaculture should not be regulated or that the environment should not be protected. On the contrary, strict regulations and environmental protection is not only consistent with but essential for successful offshore aquaculture development. What is needed is not absence of regulation but clear, consistent and efficient regulation that provides clear guidelines for where and how offshore aquaculture will be allowed and addresses regulatory goals in a cost-effective way.

Principles for efficient offshore aquaculture policies

A basic economic principle is that government aquaculture policies should be efficient: they should not impose unnecessary costs in achieving any given regulatory objectives. Put differently, government indifference to regulatory efficiency has the potential to significantly slow the development of aquaculture. Economic theory suggests that basic conditions for efficient offshore aquaculture policy include:

- Policies should be clear and stable. Regulatory uncertainty – the risk that planned offshore investments will not be approved or that regulations may change and impose additional costs and/or delay – reduces incentives for firms to invest in aquaculture.

- Policies should avoid unnecessary delay. The longer the time from when an investment is made to when an economic return is realized, the lower the rate of return on the investment. To the extent possible, government should respond rapidly to applications for leases and operating permits.
- Site leases should be well defined and transferable. Leases should be *well defined* so that farmers have a clear understanding of how and for what period of time they will be able to use a site. They should be *transferable* so that they will be operated by the most efficient farmers, who are able and willing to pay the most for the sites.
- Policies should regulate outcomes rather than inputs. If the goal of regulation is to achieve a certain outcome (such as maintaining water quality or limiting escapes), to the extent possible government should allow industry to seek the most cost-effective way to achieve the outcome rather than mandating a particular way of achieving it.

Principles for offshore aquaculture regulatory institutions

Policies affecting offshore aquaculture may be developed by a wide variety of government institutions: executive, legislative and judicial agencies and bodies at local, regional, national and international levels of jurisdiction. What kinds of institutions have authority and responsibility to develop policies affecting offshore aquaculture will affect what kinds of policies are developed.

In general, offshore aquaculture is more likely to develop if regulatory institutions have the following characteristics:

- Clear responsibility and authority. There should be clear responsibility and authority for the development of leasing and regulatory policies for offshore aquaculture policy. If no agency has both responsibility and authority to develop these policies, they will not be developed and offshore aquaculture will not happen.
- Balance of perspectives. Institutions should provide a mechanism for society to consider and balance both costs and benefits of offshore aquaculture. If agencies are only concerned with minimizing any costs or risks of aquaculture, the simplest way to do so will be to not allow it.
- Appropriate jurisdiction. Policy authority should be at levels which can consider and balance local, regional and national interests.

Challenges for offshore aquaculture

Because it is new, offshore aquaculture may face several significant policy hurdles. These include lack of an established leasing and regulatory framework; lack of clearly defined responsibility and authority for creating a leasing and regulatory framework and lack of existing stakeholder groups with a strong interest in supporting offshore aquaculture. In contrast, groups which oppose offshore aquaculture may be well established and may have agency support.

Overcoming these challenges will require that offshore aquacultures supporters make the case effectively that offshore aquaculture can be environmentally sound and economically beneficial. FAO can play a role in supporting the development of responsible offshore aquaculture by collecting, analyzing and disseminating information about the technical feasibility and potential environmental and economic benefits of offshore aquaculture.

EMPIRICAL ECONOMIC ANALYSIS OF OFFSHORE AQUACULTURE

To move beyond theoretical analysis such as that presented in this paper to empirical analysis of the prospects for or implications of offshore farming of particular species in particular locations requires the development of models based which explicitly incorporate data and assumptions about variables such as expected costs and prices and relationships such as fish growth functions and market supply and demand. Such models may range from simple spreadsheets, based on rules-of-thumb assumptions about expected average costs and prices, to complex models incorporating assumptions about factors such as feed conversion ratios, fish growth rates, and the timing of capital expenditures. In general, more complex models may be used to address more complex questions but require more assumptions, cost more to develop and may be harder to understand.

Empirical economic analyses of offshore aquaculture have several potential benefits for industry and government:

Systematic thinking. Economic models require systematic thinking about costs and revenues. This is difficult when farms do not yet exist for which costs and prices can be observed, but it is still essential.

Sensitivity analysis. Models provide a tool for testing the implications of changes in key assumptions such as feed costs or growth rates. In thinking about economic viability, what is important is not just using the best available assumptions, but also thinking about the range of uncertainty in model outputs associated with uncertainty about key assumptions.

Optimization analysis. Investors face numerous choices in the design of a fish farm, such as scale. Economic models can be used to explore tradeoffs between different design choices and to examine the implications of how farms are regulated.

Economic impact analysis. Economic models of farming operations can provide the starting assumptions for analysis of economic impacts of offshore farming, such as the jobs and income which might be created by offshore farming, both directly and indirectly.

Most of the publicly available empirical economic models for offshore aquaculture have been developed by universities and research institutions in the United States of America. They cover a range of species and geographic regions, e.g. Atlantic cod, sea scallops and blue mussels in the Northwest Atlantic (Jin, Kite-Powell and Hoagland, 2005; Kite-Powell, Hoagland and Jin, 2001); finfish in the Gulf of Mexico (Posadas, Bridger and Costa-Pierce, 2001); Pacific threadfin in Hawaii (Kam, Leung and Ostrowski, 2003); bluefin tuna in the U.S. East Coast (Shamshak and Anderson, 2009); snapper in Puerto Rico (Brown *et al*., 2002); rock bream in the Republic of Korea (Lipton and Kim, 2007); and gilthead seabream in the Canary Islands and the Mediterranean (Gasca-Leyva *et al*., 2001).

In general, these models describe the biological, environmental, economic, and regulatory conditions under which offshore aquaculture may become profitable. A useful contribution of FAO to the development of offshore aquaculture might be to assist in the development of prototype empirical economic models for species and geographical regions for which information is lacking. Industry and governments alike could use the results of these analyses in planning for particular types of offshore farms. Over time, as more experience is gained in offshore aquaculture and more data are collected from actual operations, empirical analysis will become relatively easier and cheaper.

RECOMMENDATIONS FOR FAO

What lessons may be drawn from this economic analysis about how FAO can best support the responsible development of offshore aquaculture? This analysis is concluded with three broad recommendations.

1. FAO should encourage and facilitate the development of offshore aquaculture, but should not oversell it.

The true test of whether, where and when offshore aquaculture is a good idea is the market. Although it seems highly likely that eventually large-scale aquaculture production will occur offshore, helping to meet food demands of a larger and wealthier world population, this does not necessarily mean that offshore aquaculture is currently economically viable on a large-scale. That has yet to be demonstrated.

At this stage the most appropriate strategy for FAO is to continue to collect and disseminate information about the potential for offshore aquaculture and to encourage Member states to create enabling regulatory frameworks under which investors can test that potential.

2. Probably the most effective role FAO can play is in helping governments obtain information they need to understand the potential of offshore aquaculture and to plan for and promote its responsible development.

Typically, private sector companies considering specific offshore aquaculture development opportunities have needs for detailed and specific information about potential sites, technologies, species and markets. FAO is not in a position to provide this kind of specific information at the needed level of detail. Private sector fish farmers and consultants can best develop this information themselves.

In contrast, governments, which will play a critical role in establishing an enabling regulatory framework for offshore aquaculture have a significant need for information on what kinds of offshore aquaculture might have potential, its potential benefits and costs and how they can best plan for and promote its responsible development.

FAO is well suited to help provide this information by doing things it does regularly and well, including:

- Support of technical studies by experts.
- Hosting meetings for sharing information among technical experts and government officials.
- Facilitating efforts to discuss and establish consensus on international issues related to offshore aquaculture, such as the development of aquaculture in international waters.

Specific activities that could be particularly helpful include:

- Periodic studies demonstrating that offshore aquaculture is technically and economically feasible and environmentally sound, based on case studies of actual operations.
- Development of prototype empirical economic models of offshore aquaculture for particular species and/or geographical regions.
- Development of examples of permitting and regulatory guidelines for offshore aquaculture which could be used as starting points by governments.
- Facilitating technical training of government officials responsible for key decisions affecting offshore aquaculture.
- Collecting data on offshore aquaculture production, by country and species. Note that this would require developing definitions of "offshore," or potentially multiple "offshore zones," based on objective indicators such as distance from shore. Until this is done, it will be difficult to know the extent to which offshore aquaculture is actually developing. Initially, while offshore aquaculture remains in an early stage of development and while definitions remain unclear, it may not be possible to develop formal data series, but periodic surveys of member countries could provide indicators of the approximate scale of current or expected future production.

3. Analyses of markets and marketing specifically for offshore aquaculture should not be a priority for use of FAO resources at this time.

Clearly, markets are important for offshore aquaculture. As discussed earlier, offshore aquaculture will develop on a significant scale only for species for which demand is sufficiently strong to support prices high enough that offshore farming is profitable at volumes which cannot be satisfied by production from lower-cost sites. But what FAO can do either to create this demand or help entrepreneurs learn about market opportunities is relatively limited.

Seafood markets are dynamic and can change fast. Markets develop in part because producers invest significantly in developing them. Market information, about who may be willing to buy different products and what they are willing to pay for them is valuable and often proprietary. There is intense competition for markets within the seafood industry, both among countries and often among different firms within countries. Typically, industry and national organizations are likely to be more effective in collecting detailed market information and developing marketing strategies to best take advantage of the opportunities.

FAO and its associated institutions (Eurofish, Infofish, etc.) presently have a variety of programmes and efforts which play a useful and effective role in developing and disseminating market information and in assisting with marketing efforts, primarily at the level of initial market information gathering and development. These efforts should continue. But there are no obvious *new* market-related activities which should be a high FAO priority for facilitating offshore development at this time.

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Governance in marine aquaculture: the legal dimension

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ABSTRACT

In recent years, mariculture aquaculture, also called marine aquaculture or the rearing of animals and plants in brackish and marine environments including coastal, off-the-coast and offshore areas, is playing an increasingly important role in feeding humanity and making contributions to the economies of a number of countries around the world. Most mariculture operations occur in coastal sheltered waters, which are within national jurisdictions. Because marine aquaculture competes with many other activities close to the coast, operators increasingly tend to move fish farms to more distant areas while pushing governments to allow new operations further from the coast. This paper argues that, as aquaculture operations extend further offshore, and especially as they extend to the high seas, serious issues of law and governance arise. The general principle of freedom of the seas almost certainly includes the right to conduct marine aquaculture, but public international law affects mariculture only in minor ways. Mariculture is incidentally affected by a number of provisions of general international law and by treaties which were designed to deal with other problems, particularly those concerning fisheries or the marine environment. The existing applicable principles of international law and treaty provisions provide little guidance on the conduct of aquaculture operations in these waters. This results in a regulatory vacuum as aquaculture activities extend from a state's Exclusive Economic Zone to the high seas. There are a number of options to fill this vacuum. It is possible that states might extend existing regulatory regimes to mariculture operations conducted by their nationals on the high seas. It would be desirable to create a treaty concerning mariculture on the high

seas, but this is likely to be very long-term project. In the interim, the most promising approach would be to adapt a number of existing organizations and practices, such as Regional Fisheries Organisations and the FAO Code of Conduct for Responsible Fisheries (CCRF) to include mariculture.

INTRODUCTION

Aquaculture continues to expand more rapidly than all other animal producing food sectors at a time when there are increasing concerns about the maintenance of wild fish stocks (UN News Centre, 2003). It is also clear that a growing shortage of land and access to clean water threatens to impose limits on the growth of freshwater aquaculture. Both of these factors have contributed to a significant interest in the rapidly growing field of marine aquaculture (referred to in this paper as "mariculture"[1]).

Traditionally, mariculture was carried on in bays and inlets very close to the shore. However, mariculture is increasingly pursued at a greater distance from the shoreline and it is now feasible even on the high seas.

Inshore aquaculture[2] was always seen as a matter entirely within the national jurisdiction of the coastal state and posed few questions in international law. As mariculture extends further from the shore, it begins to have greater implications in international law and to create corresponding limitations on the sovereign power of the coastal state. When ultimately it is carried out on the high seas, the jurisdiction of the coastal state is almost entirely extinguished and any governing rules are found almost solely in international law.

The experiences of coastal states in managing traditional mariculture provide vital lessons as the industry extends further out to sea. The management of mariculture in national waters has exposed a myriad of governance issues relating to policy, legal and regulatory questions and administrative and institutional design. It is vital to bear these issues in mind when considering the potential problems posed by mariculture that is carried out far from the shore. Many of these issues remain equally important when mariculture moves to the high seas, beyond the jurisdiction of the coastal state. By definition, the coastal state does not have jurisdiction over the high seas, but most of the problems that arise from mariculture in national waters continue to exist.

This study is concerned with both national and international issues in mariculture that is carried out at increasing distances from the shores of the coastal state. The purposes of this study are to:

1. Make an inventory of the governance issues that arise from mariculture in national waters, determine widespread shortcomings in schemes of national regulation and suggest critical elements of successful governance schemes.
2. Examine the applicability of the critical elements where mariculture is carried out in waters beyond national jurisdiction and, where they are applicable, discuss how those elements can be imposed and enforced while still preserving the interests of developing countries.
3. Analyse the international and regional regimes that govern mariculture on the high seas, their shortcomings and problematic issues.
4. Suggest options to improve the governance of high Seas aquaculture, including policy, institutional and legal and regulatory mechanisms.

In order to achieve these purposes, the study will consist of four substantive sections on: (i) the impact of international law on mariculture; (ii) on national regulations of

[1] Some experts define mariculture as the rearing of animals and plants in the ocean only. Others describe it as a segment of aquaculture that takes place in brackish and marine environments including outside the ocean.

[2] Aquaculture carried out in the internal waters or territorial sea of a coastal state. These concepts are discussed in more detail in the following sections of this paper.

mariculture; (iii) on issues that arise in mariculture on the high seas; and (iv) a section that suggests options to improve the governance of mariculture on the high seas.

THE IMPACT OF INTERNATIONAL LAW

In contrast to the specialized body of international law that has evolved in the area of fisheries, there is no international law of aquaculture or mariculture.

Like many other activities, aquaculture and, especially mariculture, is incidentally affected by aspects of international law that were designed to deal with other problems. Mariculture can be affected by a number of provisions of general international law, such as the developing regime for the protection of the marine environment (Long, 2007) and by treaties. Many treaties create general obligations that can affect state management of mariculture. In particular, the 1982 United Nation Convention on the Law of the Sea (UNCLOS) requires states to prevent, reduce or control pollution of the marine environment from a number of specified land-based sources.

Although mariculture has not been the subject of treaties of general application, it has been affected by action taken and other treaties, particularly those that deal with fisheries or the marine environment. For example the Convention for the Protection of the Marine Environment in the North-East Atlantic (commonly known as the OSPAR Convention) has resulted in a number of initiatives designed to minimize the impact of aquaculture on the marine environment.

The OSPAR Commission has been active in identifying concerns about the impact of mariculture, seeking information from its Contracting Parties and calling on them to adopt the best available techniques and environmental practices (Long, 2007). Commentators have also noted that other treaties, such as the 1992 Convention on Biological Diversity, have potential application to mariculture (Wilson, 2004). In addition, codes of practice, such as the FAO Code of Conduct for Responsible Fisheries (CCRF), which have no binding legal effect unless incorporated into national law, can set out principles and standards for the development of marine aquaculture.

It is unlikely that inshore mariculture will often have sufficient international dimensions to conflict with international obligations of this nature. However, as coastal states permit mariculture at ever increasing distances offshore, there is a correspondingly greater likelihood that their activities will begin to be affected by international obligations.

International law deals with marine activities by placing geographical areas of the sea into a number of categories ranging from internal waters to the territorial sea to the Exclusive Economic Zone (EEZ) and ultimately to the high seas. The potential impact of international law on mariculture will be considered with reference to each of these zones.

Internal waters

The UNCLOS defines the territorial sea as the area of the sea that lies beyond a "baseline". The baseline is best understood initially as the low water mark of the coastal state (LeGresley, 1993). However, in order to deal with the variety of indentations found in a coastline, such as bays, estuaries, and fjords, the UNCLOS allows coastal states to determine where the territorial sea begins by drawing straight baselines that follow the general trend of the coast. All waters to the landward side of the baseline are the internal waters of the coastal state. The coastal state can exercise essentially the same rights of sovereignty over its internal waters as it does over land, subject to rare cases in which foreign vessels may have a historical right to pass through those waters. For the purposes of mariculture, the coastal state has the same freedom to regulate operations in internal waters as it does in respect of land-based operations.

The territorial sea

The UNCLOS is explicit in extending the sovereignty of a coastal state beyond its land and internal waters to its territorial sea (1982 UNCLOS, Art.2 [2]). At first sight, this principle suggests that there is no distinction between the jurisdiction of the coastal state over internal waters and its jurisdiction over the territorial sea. However, in the territorial sea, the sovereignty of the coastal state begins to be tempered by international obligations. Notably, ships of all states have the right of innocent passage through the territorial sea and the coastal state has the concomitant obligation to publicize navigational hazards.

This restriction only limits mariculture activities that might be a threat to navigation and, at most, it requires the coastal state to deal with the navigational aspects of pens and cages. The coastal state is entitled to legislate in order to protect facilities and installations, including mariculture projects, within the territorial sea, but it must give due publicity to its laws and regulations (1982 UNCLOS, Art.21[4]). International law does not impose other general restrictions on how the coastal state manages mariculture within the territorial sea.

The exclusive economic zone

The UNCLOS recognizes the existence of an EEZ, which extends 200 nautical miles (370.4 km) seaward from the baseline and can be claimed by the adjacent coastal state. Most states have claimed the maximum permissible EEZ, although in some cases it has been described as an Exclusive Fishing Zone. The differing terminology has no significant practical consequences.

The UNCLOS exhibits a greater international interest in the EEZ than in the territorial sea. The coastal state is not described as exercising sovereignty over the EEZ, but it has only "sovereign rights" for the purpose of exploring and exploiting, conserving and managing the natural resources, whether living or non-living, of the waters within the EEZ (1982 UNCLOS, Art.56 [1][a]). In addition, the coastal state has jurisdiction over the establishment and use of artificial islands, installations and structures (1982 UNCLOS, Art.56 [1][b][i]).

The sovereign rights to manage the natural resources of the EEZ undoubtedly allow the coastal state to establish mariculture operations in the EEZ. The right to establish installations and structures is accompanied by the right to establish safety zones around them which are sufficient to protect mariculture operations. Sovereign rights also allow the coastal state to regulate and manage mariculture as it sees fit, but the international interest in the EEZ has placed additional obligations on those regulatory and management rights. Those obligations and rights take two principal forms that deal with pollution control and the management of straddling and highly migratory fish stocks. Each obligation will be considered in turn.

The obligation to control pollution

An initial reading of the UNCLOS suggests that pollution in the EEZ is a matter for the coastal state alone, even if it has international implications. Article 56 (1)(b)(iii) states that within the EEZ the coastal state has jurisdiction with regard to the protection and preservation of the marine environment. However, developments since 1982 have shown that this provision can create rather than exclude international obligations by emphasising that where states have jurisdiction, they must exercise it in a manner that achieves agreed international purposes.

For example, the Rio Declaration, adopted at the United Nations Conference on Environment and Development in 1992 (U.N. Doc. A/CONF.151/26 [Vol. I]), incorporates both the theme of sustainable development and the precautionary principle. Principle 3 states that: "The right of development must be fulfilled so as to equitably meet development and environmental needs of present and future generations." Principle 15 provides that "where there are threats of serious irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation."

Although not legally binding, these principles place a constraint on coastal states when exercising their sovereign rights under Article 56. They can undoubtedly permit mariculture activities, but they are obliged not to do so in a manner that threatens sustainability or the precautionary principle.

Migratory and straddling fish stocks

Articles 63 and 64 of the UNCLOS recognized that the sovereign rights of the coastal state within the EEZ had to be limited where they had an impact on highly migratory species and on fish stocks that migrated to and from the EEZ of the coastal state and another state or between the EEZ and the high seas. Both articles contemplated that these questions would be resolved by subsequent agreement. The agreement, commonly known as the Fish Stocks Agreement (1995) (U.N. Doc. A/CONF.164/37), was a major step in this resolution.

The Agreement has commanded a high degree of support, and places five requirements on the parties, which can limit their freedom to authorise mariculture activities within the EEZ. The relevant requirements are to:

1) adopt measures to ensure the long-term sustainability of straddling fish stocks and highly migratory fish stocks;
2) adopt, where necessary, conservation and management measures for species belonging to the same ecosystem;
3) minimize pollution, waste, discards and impacts on associated or dependent species;
4) assess the impacts of fishing, other human activities and environmental factors on target stocks and species belonging to the same ecosystem;
5) protect biodiversity in the marine environment.

The Fish Stocks Agreement addresses a number of issues that are often controversial in the management of aquaculture. It imposes legal constraints on how states which have acceded to the Agreement manage mariculture within the EEZ, because a failure to comply with these requirements amounts to a contravention of the Agreement.

The high seas

The high seas consist of those areas of the sea beyond the EEZ in which coastal states have no jurisdiction (LeGresley, 1993). Although states lack sovereign rights over the high seas, they have some well-defined freedoms and obligations.

All states have freedom of navigation and fishing on the high seas, as well as the freedom to construct artificial islands and other installations permitted under international law (1982 UNCLOS, Art.87 [1][d]). There is little doubt that the freedom to construct artificial islands and other installations is sufficient to permit mariculture operations that employ cages or pens on the high seas. Mariculture operations are permitted under international law, and intrude less on the management of the high seas than artificial islands or other installations. They are less intrusive than activities which are widely assumed to be permissible beyond the EEZ. Some of these include those activities that are intended to produce or support the production, transportation or transmission of energy. In the United States of America, they can be permitted by Congress on the outer continental shelf under Section 388 of the Energy Policy Act of 2005 (Eberhardt, 2005).

Although it is safe to conclude that mariculture can be carried out on the high seas, there is a clear obligation to ensure that it does not conflict with the rights of other states. In particular, the UNCLOS imposes many duties on states to preserve and protect the marine environment (Kalo, Hildreth and Christie, 2007).

Four of these duties are particularly relevant to mariculture on the high seas:

1) All states have an overriding obligation to protect and preserve the marine environment and to take all measures consistent with the Convention that are necessary to prevent, reduce and control pollution of the marine environment from any source. The requirement for states to take anti-pollution measures is limited to using the best practicable means at their disposal and in accordance with their capabilities (1982 UNCLOS, Art.192 and 194 [1]). This limitation suggests that developing countries may be less accountable under these articles than their counterparts in the developed world.
2) States must take all measures necessary to prevent the intentional or accidental introduction of species, alien or new, to a particular part of the marine environment, which may cause significant and harmful changes (1982 UNCLOS, Art.196).
3) States are required, either directly or through competent international organizations, to monitor as far as practicable the risks or effects of pollution of the marine environment (1982 UNCLOS, Art.204).
4) When States have reasonable grounds for believing that planned activities under their jurisdiction or control may cause substantial pollution of, or significant and harmful changes to, the marine environment, they must, as far as practicable, assess the potential effects of such activities (1982 UNCLOS, Art.206).

Thus, international law emphasizes that, although mariculture can be carried out on the high seas under international law, its conduct is accompanied by significant international obligations. In this respect, mariculture is similar to other activities, such as shipping and fisheries, in which states can exercise their rights on the high seas, subject to rules derived from customary international law and treaties.

However, mariculture differs from those activities in two respects. Firstly, it is subject to international obligations that are far less specific than those applicable to shipping and fisheries. Secondly, it is relatively easy to trace international responsibility when offences relating to fisheries and navigation are detected, because ships are required to fly the flag of one state and assume the nationality of that state. The responsibility for certain offences is then assigned to the flag state. It is potentially more difficult to determine where the responsibility lies if mariculture on the high seas leads to a violation of one of the international obligations described in this section. In contrast to shipping, there is no requirement that cages or pens must be registered in a given state, to which it is then possible to assign responsibility for any violations of international law.

Two provisions of the UNCLOS alleviate this concern by allowing a link to be made between mariculture operations on the high seas and state responsibility. The Convention establishes the principle that a state is responsible for its nationals by providing that: "All States have the duty to take, or to cooperate with other States in taking, such measures for their respective nationals as may be necessary for the conservation of the living resources of the high seas" (1982 UNCLOS, Art.117). This provision is supported by a clear statement of the state's obligations:

- States are responsible for the fulfilment of their international obligations concerning the protection and preservation of the marine environment. They shall be liable in accordance with international law.
- States shall ensure that recourse is available in accordance with their legal systems for prompt and adequate compensation or other relief in respect of damage caused by pollution of the marine environment by natural or juridical persons under their jurisdiction (1982 UNCLOS, Art.235 [1][2]).

Although it may not initially be clear who is responsible for a particular mariculture operation on the high seas, once it is possible to identify the nationality of the operator, Article 235 establishes state responsibility to ensure that obligations for the protection and preservation of the marine environment are observed.

The following section discusses how states have exercised their jurisdiction by regulating mariculture in their internal waters, the territorial sea and the EEZ, with a view to examining, in the section on governance of mariculture on the high seas, how key elements of those regulatory schemes can be made applicable to the high seas.

THE GOVERNANCE OF MARICULTURE IN NATIONAL WATERS

The first part of this section this will set out the central issues involved in the governance of aquaculture, based on the experience of governments in enacting schemes for the regulation of mariculture in national waters over recent decades. The second part will identify common shortcomings in the governance of mariculture that threaten to prevent this form of aquaculture from achieving its full potential.

Governance issues

Establishing control: permit and licence systems

The cornerstone of any effective scheme to regulate aquaculture is the establishment of a licence or permit system. The underlying principle is that no person can carry on mariculture without first obtaining a licence from the state. The requirement of a licence confirms that the state has the right to regulate all mariculture activities and to prosecute those who carry on an operation without fulfilling the requirements. In particular, the requirement of a licence enables the state to directly regulate the operator of a mariculture facility, to enforce the basic rules of mariculture, to restrict the location and number of mariculture facilities and to obtain public input on projected developments.

These purposes are commonly achieved through the following techniques:

- Requirements of licences enable the state to assess the capacity of the applicant. For example, in Namibia, the Minister may examine the technical and financial ability of the applicant in considering an application for a licence (Namibia Act, s. 12[3][a]). Under the Norwegian Aquaculture Act of 2005, it is necessary for the applicants to demonstrate that they have the necessary professional qualifications, either through formal education or work experience, before obtaining a licence, including the necessary knowledge of how to prevent, detect and limit the escape of fish (FAO, 2012).
- Requirements of licences require applicants to show in advance how they will meet all regulatory requirements (Long, 2007) and can go so far as requiring the applicant to supply an economic guarantee to repair certain types of damage that might occur as a result of the mariculture operation (FAO, 2012).
- Requirements of licences enable the state and others to identify all the operators of aquaculture or mariculture facilities by maintaining a register of licences. The register can allow an assessment of all the rules applicable to those facilities by including copies of all licences that have been issued (Long, 2007), as well as, records of any transfers of licences. The most sophisticated registry system can also permit the registration of mortgages or other financial instruments which an operator has granted against the security of an aquaculture licence (FAO, 2012).
- Requirements of licences provide a means of enforcing the basic rules applicable to a mariculture operation through the attachment of conditions to the licence. Although it is preferable for the governing legislation to stipulate the most important rules relating to tenure and environmental responsibility, the conditions of the licence are appropriate for setting out site-specific requirements and incorporating codes of conduct that will govern the operation (Nambia Act, Section 14[4]).
- Requirements of licences enable the state to control the number of licences issued, so as to avoid excessive concentration of mariculture facilities, as well to supervise the geographical distribution of licences. This requirement can ensure that mariculture is established only in suitable locations and that interference with other activities is minimized (FAO, 2012).

- In almost all modern legislation, the requirement of a licence is used to obtain public input on the proposed operation. It is now commonplace for legislation to require the applicant to provide notice of its application to the public and to allow the members of the public to submit objections or representations to the ultimate decision maker (Namibia Act, Section 12[4]).

The selection of the site and the tenure of the operator

As indicated in the previous section, the licensing system provides a strong basis for ensuring that mariculture is carried out only at appropriate sites. The applicant should be required to provide information about the relationship of the proposed site to other sites and activities in the area and to any marine protected areas, as well as its relationship to other public activities (FAO, 2012).

In order to avoid a close examination of the appropriateness of the proposed site in every application and the dangers of discretionary decision-making, it is helpful if the government designates in advance areas of water that are suitable for mariculture. It is also vital that the licence, in combination with the governing legislation, clearly states the nature of the tenure of the operator to an extent that will allow the mariculture operation to be financed, to flourish over an extended period and to enable other people to be excluded from the area (Percy and Hishamunda, 2001).

The operator's exclusive rights to the site of the project can be realized in a number of different ways. Ireland vests ownership of the aquaculture resource in the licensee. In contrast to other marine resources, the relevant Irish legislation provides unequivocally that "the ownership of any fish... specified in the licence... vests in the licensee" (Long, 2007). The Norwegian legislation states that a person who holds an aquaculture licence has "exclusive rights to the withdrawal and capture of the released species at the site" and allows the relevant ministry to limit or ban any traffic on or other use of the site and adjoining areas, including fishing, where this is necessary to protect aquaculture production. Similarly, a licence in Namibia confers "an exclusive right to farm and harvest aquaculture products within the site defined in the licence" (Namibia Act, Section 14[2][3]).

The legislation must also address the length of the licensee's tenure. The Irish legislation allows the licensing authority to grant a licence for a period of up to 20 years, depending on the nature and production cycle of the aquaculture operation and the applicant's business plan (Long, 2007). Other countries give no guidance on the duration of a license, but leave that determination to the approving authority (Namibia Act, Section 14[4][j]). Under this model, it is vital for the approving authority to grant licences for a sufficiently long-term to provide the security of tenure that will encourage the development of the industry. Instead of relying on short-term licences, the regulator should retain control through its power to revoke licences if necessary upon the commission of certain specified offences. When dealing with the territorial sea or the EEZ, it is also important to ensure that the governing legislation grants the government the power to authorize the use of offshore waters by the licensee (Baur, Eichenberg and Sutton, 2009).

Measuring the environmental sustainability of the project

Even after an appropriate site has been chosen, the requirement to obtain a licence or permit prior to engaging in an aquaculture project provides the regulator with the opportunity to consider the environmental sustainability of the proposal. The threshold question concerns the extent of the information that the applicant must submit to enable the regulator to decide whether and under what conditions the proposal can be accepted.

Existing regimes for regulating mariculture in national waters provide a large range of requirements for the submission of environmental information in licence applications.

The requirements can be as extensive as a full environmental impact assessment or as minimal as the provision of a basic operational plan. It is important for the governing legislation to state explicit criteria for determining how much information an applicant must provide both to ensure that applicants are fairly treated and to recognise the great expense that can result from the requirement of an environmental impact assessment. National regimes tend to recognize the broad principle that an environmental impact assessment should be required only for those projects that create a genuine risk of environmental damage.

The European directive on environmental assessment provides an example of this approach. Applications for aquaculture licences are not automatically subjected to an assessment, but aquaculture belongs to a category of projects for which an environmental assessment is required if there are likely to be significant effects on the environment.

The potential for significant effects on the environment is measured by factors including the nature, size or location of the proposed project (Directive 85/337/EC, as amended by Directive 97/11/EC of 3 March 1997). National legislation implementing the European directive reflects this approach by subjecting only certain categories of aquaculture projects to an assessment. In Ireland, for example, an environmental impact assessment is required where an applicant proposes to introduce a new species into the marine environment. This is a common requirement in national regulatory schemes and is also found in Namibia, which requires an environmental assessment where a new or genetically modified aquatic organism is to be introduced into Namibian waters (Namibia Act, Section 7). This type of provision can be accompanied by a direction to the regulator to have regard to the likely effects of the proposed aquaculture on wild fisheries, natural habitats and flora and fauna (Long, 2007).

In Ireland, applicants are required to submit an environmental impact statement for other projects, because of their scale and location, as well as for certain classes of aquaculture where the regulator or, in some applications, the Minister, considers that the proposed project is likely to have significant effects on the environment. The applicant must make copies of its environmental impact statement available to interested parties (Long, 2007).

In Norway, the general principle is that an aquaculture licence will be granted only if the aquaculture project presented is "environmentally responsible". The application of this principle gives the relevant Minister the power to require that any applicant for an aquaculture licence shall conduct necessary environmental surveys and document the environmental condition of the site. As a general principle, an environmental impact assessment is required for large-scale aquaculture installations or hatcheries, if they are likely to have significant effects on the environment.

The Norwegian legislation also illustrates that type of information that an applicant must submit where the project is not subjected to a full environmental impact assessment. The Licensing Regulations require an applicant to provide information regarding the currents at the proposed site, a map of the proposed site and the results of an environmental survey of the sea bottom at the site (FAO, 2012).

In other countries, if the project is not one which attracts a mandatory environmental assessment, the governing legislation sometimes leaves the type of information to be submitted by an applicant to the discretion of the regulator (Namibia Act, Section 12[1]).

Control of water quality

The permit approval process provides an ideal opportunity to deal with any concerns about water quality arising from a proposed mariculture facility. Net pens or cages are used widely in offshore aquaculture and they can release high levels of solids and wastes, composed of feces, uneaten foods, antibiotics and pesticides. Virtually, all national regulatory schemes deal with wastes, although at different levels of detail.

At a basic level, some countries leave the control and waste subject to the discretionary inclusion of conditions in licences. Namibia permits the Minister to issue a licence subject to conditions relating to water quality (Namibia Act, Section 14[4][c]) and Ireland grants the licensing authority discretion to make a license subject to whatever conditions it thinks appropriate, as long as they are in the public interest. In the Irish legislation, the authority is specifically empowered to include conditions relating to the protection of the environment and the control of discharges (Long, 2007).

Other national legislation is much more detailed. In Norway, an applicant for an aquaculture licence is first required to obtain a permit to discharge waste water. The permit will require that residues must remain within acceptable limits (FAO, 2012). One of the most detailed regimes was contained in National Offshore Aquaculture Bills, which were introduced in the United States of America in 2005 and 2007. Although neither of these bills became law, they provided a very strong basis for regulating waste from mariculture operations.

The 2007, Bill would have subjected aquaculture facilities to the Clean Water Act, which directs the Administrator to issue procedures and guidelines for permitting aquaculture projects. The Environmental Protection Agency issued regulations under the National Pollutant Discharge Elimination System, which defined concentrated aquatic animal production facilities as point sources of pollution.

Following this development, the Agency established categorical effluent guidelines for the aquaculture industry. The strongest feature of the proposed system was its focus on requirements to minimize the release of pollutants, including the proper management of feed, the storage of drugs and pesticides and the disposal of feed bags, nets etc and the need to minimize the discharge of dead animals and parts. This preventive approach would have been supplemented by stringent siting requirements for new facilities and regular inspections (Powers and Smith, 2009). Despite the fact that this Bill has not become law, its provisions for dealing with waste are notable because they establish a close link between aquaculture and provisions of the Clean Water Act that are both powerful and effective.

Enforcement of the regulatory scheme

Virtually, all national legislation dealing with aquaculture or mariculture sets out a list of general rules for the conduct of operations and stipulates penalties that are applicable in the event of infractions. However, the rules can be almost meaningless unless they are accompanied by an effective enforcement scheme.

There is no substitute for legislative provisions that establish an adequately financed and effective inspectorate charged with the enforcement of the governing legislation. It is also vital that the legislation should provide the inspectorate with the basic legal powers required to enable them to carry out their functions, such as the power to enter privately owned facilities, inspect records, take control of evidence and take immediate remedial action where necessary (Namibia Aquaculture Act, Section 37). These powers are the cornerstone of an enforcement scheme, but it is necessary to face the reality that even in highly developed countries there are complaints about the lack of a specialized and effective inspectorate (Long, 2007).

The licensing system can supplement the governing legislation in a number of ways. It can augment the general provisions set out in the statute with more detailed rules applicable to individual operations. In practice, the supplementary rules have typically been used to deal with four issues in particular: the incorporation of codes of conduct applicable to the licensee; rules relating to the escape of farmed animals; the reporting and treatment of diseases; and emergency responses. In addition, licences can supplement the powers of the inspectorate by providing the information, foundation required for effective enforcement. Each of these topics will be dealt with in turn.

1) **Codes of conduct** – Legal regimes for the conduct of aquaculture are often supplemented by documents that may be known as codes of conduct, codes of practice or technical guidelines. The codes allow governments to address a problem which is pervasive, but which causes particular difficulties in developing countries. Limited budgets can mean that regulators are not equipped to insist on proper operational standards for individual aquaculture operations. The incorporation of a licence term which provides that operations must be conducted in accordance with a specified code of conduct can alleviate this problem, provided that there is some sensitivity to ensure that the guidelines contained in the relevant code are suitable to the needs of the particular country. The incorporation of a code into a licence is a useful means of providing the code with the force of law (Percy and Hishamunda, 2001).

2) **Escapes** – The initial decision on granting the licence should incorporate precautions to minimize the risk of escapes. The operational requirements of the licence often include an immediate duty to notify the regulator if there is a suspicion that fish may be escaping or if escapes have been detected and impose a duty on the licensee to take effective action in the event of an escape. The notification requirements are typically accompanied by supplementary provisions that require the licensee or authorise other persons to recapture the escapees, although these requirements may not be effective in practice (Long, 2007).

3) **Diseases** – Licence terms also tend to impose a duty of immediate notification if a disease occurs or is suspected in the area covered by the licence. This requirement may well be supplemented by a duty to report abnormal losses or mortality among the farmed stock. In addition, the licensee should be required to keep precise records of all chemicals and antibiotics that have been used in the aquaculture operation, together with the times at which they were administered (Long, 2007). In some jurisdictions, the regulations expressly forbid the movement of stocks when there is reason to suspect a contagious disease (FAO, 2012).

4) **Emergency responses** – The governing legislation frequently requires the licensee to keep an up-to-date emergency plan, although this requirement can also be contained in the terms of the license. The plan must typically deal with responses to escapes and disease, together with other eventualities such as sudden pollution, harmful water temperatures or invasions of algae or jellyfish (FAO, 2012). The licensee should be required to notify the regulator immediately if it becomes necessary to implement the emergency plan.

5) **Enforcement** – Even an ideal national regime for regulating aquaculture or mariculture is of limited use unless it is accompanied by the creation of an effective and efficient inspectorate. In practice, limited financial resources often constrain the ability of the regulator to fully supervise aquaculture operations. Although there is no substitute for effective inspection, the terms of the licence can help to make the regulations more effective. It is common to require a licensee to keep detailed records of operations for a specified period and to produce them to the regulator on request. The records can deal with every aspect of the operation and include matters relating to escapes, disease, chemicals and antibiotics are set out earlier. In addition, they can require the licensee to make and record inspections of specified aspects of the operation (FAO, 2012). These steps can be of great assistance to the regulator, although they require the active cooperation of licensee. Because of their importance, it is vital to ensure that licensees indeed keep the require records and to specify meaningful penalties if they fail to do so.

Common shortcomings in national regimes

The first part of this section used some highly developed national systems to explore major issues in the governance of mariculture. Even advanced systems of national regulation suffer from some recurring problems. In most jurisdictions, there is a fragmented approach to the regulation of mariculture and difficulty in assuring an adequate level of regulatory supervision. These problems are magnified in jurisdictions with less comprehensive regimes. In addition, in some schemes of regulation in the developing world, there are particular problems that involve the assurance of an adequate level of regulation at a reasonable cost and the need to ensure that the products of mariculture can be sold in markets in the developed world. Each of these shortcomings will be addressed in turn.

A fragmented approach

A fragmented approach is one of the commonest weaknesses in the regulation of land-based aquaculture. A proponent is typically required to obtain permits from a number of government departments and is subjected to a number of different statutes. Many countries recognise this defect and seek to overcome it by providing a single window system for obtaining the necessary approvals. Even this approach does not overcome the problems of cost and delay, unless a lead agency is established to take responsibility for an application and pilot it through the regulatory requirements (Percy and Hishamunda, 2001).

The problems of fragmentation are increased in offshore areas. Countries rarely have a comprehensive approach to the governance of the offshore; and so mariculture operations are likely to be subjected to many of the same agencies that regulate onshore aquaculture, with a further layer of requirements imposed by various marine authorities. In Ireland, for example, environmental impact assessments for aquaculture projects in coastal and offshore areas are governed by six different pieces of legislation (Long, 2007).

There is even greater complexity in federal states, such as the United States of America and Canada, and in federal-like systems, such as the European Union. In federal states, mariculture may be complicated by competing regulatory efforts at both the state or local government level and at the federal level. For example, in the United States, there is increasing interest in establishing mariculture facilities in the EEZ, but the regulatory regime is unclear. States have sovereignty over waters within 3 nautical miles (5.5 km) of shore, but federally regulated activities beyond that point must, in the case of potential conflict, be consistent with the state's coastal zone management plan. As mariculture occurs further offshore, it "falls within the purview of a number of federal departments and agencies, implementing a myriad of federal laws" (Baur, Eichenberg and Sutton, 2009). At least six major federal agencies can play a role in regulating offshore mariculture in the United States of America.

A fragmented regulatory regime poses two categories of problems. Firstly, without serious coordination efforts, there is no mechanism for looking at the impact of the proposed project as a whole, rather than examining only its individual aspects. Secondly, the difficulty of complying with the requirements of many different agencies can impose significant costs and delays for applicants, thereby rendering aquaculture projects uncompetitive.

Regulatory supervision

A pervasive theme in analyses of national regulatory schemes is the need to establish an inspectorate with all the necessary powers to enter fish farms and to enforce the governing legislation. Even in some developed countries, aquaculture legislation fails to include the necessary provisions. In Ireland, for example, "a number of public representatives have expressed the view that the absence of a specialized inspectorate for the aquaculture industry is a critical omission in the legislative framework" (Long, 2007). In addition, the inspectorate must be adequately trained and funded. In the absence of a professional inspectorate, the enforcement of legislation is typically piecemeal and can involve the various government agencies which regulate different aspects of the mariculture operation. By default, in the absence of a specialized inspectorate, fisheries authorities are likely to be those most involved in policing mariculture.

The problem of inspection is even greater for developing nations. A lack of financial resources means that the agencies that supervise the various individual aspects of mariculture operations may lack an inspectorate and that a specialized body of inspectors is less likely to exist. Without a proper inspectorate, even the most sophisticated regulatory regimes are unlikely to fulfil their objectives.

Cost effective regulation

In the previous section on "Measuring the environmental sustainability of the project", it was observed that national regimes tend to recognize the principle that an environmental impact assessment should be required only for those projects that create a genuine risk of environmental damage. Some of the major exceptions to this trend are found in the developing world and they make it difficult to concentrate scarce and administrative resources on regulating difficult proposals that create a real risk of a environmental harm.

In achieving the laudable purpose of passing comprehensive environmental legislation, some countries require most or even all aquaculture projects to undergo an environmental assessment (Percy and Hishamunda, 2001). If broad requirements of this type are administered in accordance with the governing law, they can result in a cursory examination of all projects, because a lack of adequate administrative resources prevents the identification of individual projects that might pose a genuine threat to the environment. In addition, broad requirements for an environmental assessment can deter investment by imposing unnecessary costs on proponents of projects that pose only minimal risks.

Some suggestions to ensure that environmental assessments are limited to genuinely controversial proposals are of particular interest to mariculture. The simplest response was provided by the International Symposium for Sustainable Industrial Fish Farming in a document that became known as the Holmenkollen Guidelines. The Guidelines suggested that environmental impact assessments should be applied only to "large-scale" aquaculture projects (Howarth, 1999). This solution is properly criticised because it measures the potential for environmental harm through the size of the project; smaller scale projects might pose a greater environmental threat, especially if they are highly intensive and located in a sensitive area or if they involve exotic species.

The problem of determining which mariculture activities should be subjected to an environmental assessment has been a problem for all jurisdictions. The determination requires an examination of environmental risk factors. This examination has resulted in decisions that seek to eliminate the risk or to ensure that it is fully taken into account. The former possibility is illustrated in California (USA), which absolutely prohibits ocean farming of genetically modified and non-native species (California Code, 15007). Although draconian, this approach could ease the supervisory burden on administrators and allow them to focus on other important aspects of the approval process, including dealing with the regulation of feed, chemicals and antibiotics or the management of waste. The broad prohibition could be modified or abolished if experience elsewhere in the world shows that the risks created by some genetically modified or non-native species can be effectively managed.

The latter possibility of ensuring that the risk is fully taken into account is much more common and is illustrated by the Namibian example, discussed earlier. Namibia requires an environmental assessment of any proposal that involves the possible introduction of a new species or a genetically modified aquatic organism. These examples show the importance of ensuring that proposals that genuinely threaten the environment will undergo a proper assessment. They also illustrate the importance of making this decision on the basis of a realistic assessment of the regulatory resources available to the jurisdiction.

Safeguarding exports

Increasingly, national regimes for the regulation of aquaculture contain detailed provisions relating to food hygiene and food safety. In Europe, these provisions place primary responsibility for the safety of food on the producer, who is required to use a Hazard Analysis and Critical Control Points system, but national authorities are obliged to certify compliance with food law and food hygiene regulations (Long, 2007).

The enactment of complex codes dealing with food hygiene and safety is challenging for many developing countries. If they wish to enter export markets, particularly in Europe and North America, they face the challenge of incorporating the standards of the major potential importers into domestic legislation. The standards are likely to go so far as regulating many of the inputs into a mariculture operation. However, the mere enactment of standards is not enough to secure access to export markets. The importing jurisdiction is likely to require an unfailingly credible certification that there has been compliance with those standards.

At a minimum, national legislation must provide for a certification procedure and a certifying authority. In reality, access to export markets may require that the certifying authority is an agency based outside the country in which the mariculture occurs. Although this requirement is often perceived as a significant limitation on sovereignty, the producing country is effectively required to comply if it wishes to export its products.

GOVERNANCE OF MARICULTURE ON THE HIGH SEAS

As discussed in the earlier section on “The impact of international law”, no state can assert sovereignty over the high seas because they are beyond national control. The UNCLOS recognises the general freedom of the high seas and provides a non-exclusive list of individual activities that are permitted under that principle (Christie and Hildreth, 2007). As stated in the section on “The high seas” of this study, the freedom of the high seas almost certainly includes the right to conduct mariculture. The only limitations on that right are found in the general rules of public international law, in the terms of applicable treaties and in the general obligations under the UNCLOS, such as the duty to exercise the right of freedom of the seas with due regard to the interests of other states and to take the measures necessary for the conservation of the living resources of the sea (1982 UNCLOS Art.87[2], Art.117).

The applicable principles of public international law and treaty provisions may touch on aspects of mariculture, but only in minor ways. If the conduct of mariculture operations involves a breach of a principle of international law or of a provision of a treaty, a state can be held liable for the acts of its nationals under the rule of state responsibility as described in section on “The high seas”. However, it is probable that any such breach will deal only with some tangential aspects of mariculture, such as interference with navigation. The existing body of international law simply does not deal with the potential problems of mariculture that are typically included in the national regimes described in the earlier section on “The governance of mariculture in national waters”.

At the present time, it can only be concluded that there is no significant regulation of mariculture on the high seas. If mariculture does extend from a state’s Exclusive Economic Zone to the high Seas, there is a regulatory vacuum; which means that the potential problems of mariculture are almost completely neglected.

There are three potential solutions that can address the problem of a legal vacuum with varying degrees of effectiveness. The vacuum can be filled by the extension of state regulatory regimes, by the treaty making process or by the adaptation of existing organizations and practices. Each of these options will be considered in turn.

The extension of state regimes

Although states have no jurisdiction over the high seas, they are capable of exercising jurisdiction over their nationals. It is conceivable that a state could make its mariculture laws applicable to nationals who carry out mariculture on the high seas. The state has some incentive to pass legislation of this type because the UNCLOS makes it clear that a state is responsible for the actions of its own nationals.

In theory, a state could apply its regulatory regime to its nationals on the high seas in much the same way as it does within the EEZ. However, in practice, the enforcement of the regime is likely to be limited. This is because the state can enforce its regulations only against its own nationals and because of the increased costs of enforcement at a great distance from the state's own territory. It must also be recognized, as discussed earlier, that because of the lack of adequately trained and funded inspectorate, the enforcement of mariculture regulations is often difficult even in national waters and this problem can only be magnified on the high seas.

A state is also limited in the type of regime it can apply on the high seas. The state governance of marine aquaculture considered in the section above on "The governance of mariculture in national waters", dealt with aquaculture from a facilitative and a regulatory perspective. The facilitative perspective involved the state providing the operator with the necessary rights to conduct marine aquaculture operations. Although a state might enforce regulations against its nationals on the high seas, it cannot provide them with the same rights that apply in national waters. Moreover, because of the principle of freedom of the high seas, the state cannot grant any type of secure tenure to any portion of the high seas, provide for the exclusive possession of a site or even grant an effective authority for the use of a particular area of the sea.

The extension of State regimes can thus never be more than a partial solution to the regulation of mariculture on the high seas. It is probable that a number of states will not extend the scope of their legislation and, even where they do so, the effectiveness of the legislation will be nullified if the mariculture operations are carried out by non-nationals.

The creation of a treaty

In the absence of existing legal principles, new international law governing mariculture on the high seas can be created only through the making of a treaty. If there is a serious likelihood of a major extension of mariculture into the high seas, there is no doubt, as a matter of law, that a treaty would be the best solution. However, in realistic terms, this solution is unlikely to be achieved even in the medium-term future. All treaties involve a great deal of preparation, followed by prolonged negotiations to produce a final text and often a lengthy period until the required number of countries accedes to the treaty. More importantly, before a treaty can even be contemplated, it must deal with a topic that is seen to be sufficiently pressing and important to justify the attention and resources of the international community. Despite the growing importance of aquaculture worldwide, it is difficult to envisage that the international community will consider aquaculture on the high seas as an appropriate subject for a treaty for many years.

The adaptation of existing organizations and practices

The prospects of creating a new regime to regulate mariculture on the high seas are thus bleak. It is much more promising to consider building on successful existing models to achieve the required level of control. The field of international fisheries provides some of the most promising avenues for the management of mariculture.

The urgent need to manage diminishing fish stocks without significant delay required considerable innovation to overcome the laborious treaty making process. The initial UNCLOS had a glaring weakness in the management of migratory and straddling fish stocks and left this question to be dealt with by future agreements (UNCLOS, Art.63). The Fish Stocks Agreement (1995) filled this gap by providing an impetus for cooperation and compatibility in the management of fisheries within and beyond EEZs. Countries which fish for straddling or highly migratory species are required to satisfy their obligation to cooperate through existing treaties and international arrangements or through regional fisheries organizations. The Fish Stocks Agreement provides that all countries (whether or not they are parties to the Agreement) may not participate in managed high seas fisheries unless they are members of a regional fisheries organization or accept that organization's management measures.

The Agreement directs non-complying and non-party states not to authorise fishing by their vessels in managed fisheries and contains an unusually direct enforcement mechanism. Parties are authorized to take measures consistent with the Agreement and international law to deter non-parties from undermining the effectiveness of regional management measures, in some circumstances even if those measures are taken against non-party vessels (Christie and Hildreth, 2007). The Agreement was a major advance in the effort to deal with the depletion of fish stocks. It is legally controversial because it attempts to bind states, and contemplates enforcement actions against states, that are not parties to the Agreement. Nevertheless, it has been accepted widely in a short period of time. The Fish Stocks Agreement came into force in 2001 and had been ratified by 77 countries by November 2009.

One of the best prospects for the management of mariculture on the high seas is found in the regional fisheries organizations created under the Fish Stocks Agreement; and, there is already some precedent for action. In 1994, the North Atlantic Salmon Conservation Organisation (NASCO) agreed to adopt measures to protect wild Atlantic salmon from the impacts of salmon farming. In 2003, it became apparent that the 1994 measures had not been entirely effective and in the Williamsburg Resolution, NASCO adopted a much more detailed scheme to protect wild salmon. The Williamsburg Resolution deals with many of the issues found in national mariculture regimes. It requires parties to reduce escapes to a level that is as close as possible to zero, to protect wild fish from irreversible genetic change, to deal with the ecological impacts of salmon farming and the impact of disease and parasites (Long, 2007).

Although the precise legal basis of the Williamsburg Resolution is controversial, it provides mechanisms which are likely to be at least as effective as many of those found in the conventional international law of fisheries. Regional fisheries organizations have a wide geographical reach and are recognised as among the most useful international bodies dealing with fisheries. Unless properly regulated, mariculture operations on the high seas could potentially have an impact on straddling and migratory species. It is likely to be in the interest of regional fisheries organizations to impose a level of regulation on high seas mariculture that is the least similar to that found in the Williamsburg Resolution. That level of regulation can be supplemented by reference to some existing international practices.

Since the creation of the UNCLOS in 1982, it has been necessary to find ways to deal with some of its inadequacies and even to modify some of its central principles, such as the concept of maximum sustainable yield which proved ineffective in managing rapidly declining fish stocks. The FAO CCRF (1999) was a major response to this necessity and it contains a number of principles and standards for aquaculture development both within and beyond national jurisdictions (Long, 2007).

The FAO CCRF has been most effective when incorporated into national legislation. Its impact is otherwise somewhat limited, because it is difficult to enforce a voluntary code against an unwilling state. However, the existing legal scheme of the Fish Stocks Agreement provides an opportunity to do so through the principle which prevents states from participating in managed high seas fisheries unless they are members of a regional fisheries organization or accept its management measures. A substantial level of control over mariculture can be achieved if those management measures incorporate either the FAO CCRF or independent rules regulating mariculture. This level of control can be supplemented by the measures set out in the Fish Stocks Agreement to deter non-parties from undermining the effectiveness of regional management measures.

CONCLUSION

It is clear that the possibility of open ocean fish culture is being explored in a number of countries around the world. It is only a matter of time before significant mariculture operations are carried out on the high seas. Such operations can create important benefits, but experience with mariculture closer to shore shows they can also be the source of serious problems. Coastal states have frequently addressed these problems in waters that they control through comprehensive schemes of regulation.

Aquaculture on the high seas will create many of the problems that already exist in state controlled waters. Yet there is no management or regulatory regime that will apply to mariculture on the high seas. Once operations begin to occur on a large scale, vested interests will make it increasingly difficult to impose unnecessary regulations.

Although existing treaties incidentally affect some aspects of mariculture, it is irresponsible to fail to take some immediate steps to address systematically the problems that are bound to occur in the future. The ideal solution would be to begin discussions on a treaty respecting mariculture on the high seas, but this will be a long-term process. Meanwhile, preparatory work that will be helpful in creating a future treaty should begin. The preparations can involve the development of a Code for Responsible Mariculture on the High Seas by the FAO, perhaps under the umbrella of the existing CCRF. Regional fisheries organizations offer the best prospect of meeting immediate regulatory needs. They are the only multilateral organizations with the mandate, arising out of the Fish Stocks Agreement, the incentive through a shared need to safeguard wild fisheries and, in some cases, the experience to address mariculture on the high seas in the foreseeable future.

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Kona Blue Water Farms case study: permiting, operations, marketing, environmental impacts, and impediments to expansion of global open ocean mariculture

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ABSTRACT

Kona Blue Water Farms, Inc. offers an example of the integrated development of marine fish hatchery technology and open ocean mariculture. This paper presents an overview of the permitting requirements, operations and marketing, and the presumed and actual impacts on a local and global scale, and highlights some of the constraints to fulfilment of the industry potential.

Kona Blue undertook an extensive consultative process with traditional leaders, community, and conservation interests over a three-year period in acquiring the requisite Federal and State permits for the 90 acre (approx. 36 hectares) open ocean mariculture site. The company produces up to 500 tonnes of sashimi-grade highfin amberjack or Kona Kampachi® (*Seriola rivoliana*) annually, using up to eight innovative, submersible Sea Station® net pens. Operations are heavily reliant on divers, and increased automation is needed to reduce operating costs. The product is marketed as a branded open ocean raised fish, and attains high prices in both sushi and white-tablecloth restaurants across the United States of America. The species is globally distributed, and offers potential for expansion in warm waters worldwide.

The Kona Blue farm is located a half-mile offshore (approx. 0.8 km), in waters over 200 ft deep (approx. 61 m), over a sandy bottom. There are no conflicting recreational or commercial uses for this site. Ongoing monitoring of water quality, substrate beneath the pens, an adjacent coral reef and marine mammals in the area demonstrate that there is no significant environmental impact from the operation. There is no measureable impact on water quality and only minor accumulation of displaced algal biofouling immediately beneath the net pens. The adjacent coral reef retains its pristine condition, and healthy coral colonizes the moorings and rigging around the farm site. Humpback whales and

other marine mammals are neither attracted nor repelled by the operation, with the exception of some bottlenose dolphins that occasionally frequent the farm site.

Development of alternative sources of proteins and oils for feedstuffs is key to the sustainability, scalability and quality control for products in this industry. Of the many potential sources being explored, the most immediately promising are soy proteins and oils, and fishmeal and oil derived from the processing by-products of edible seafoods, such as salmon and pollock. Use of fishmeal and fish oil from the majority of targeted reduction fisheries, such as Peruvian anchovies, is justified by the less efficient alternatives for use of these products, and the increasing feed efficiencies of marine fish. The long-term goal is to ensure effective management regimes around these fisheries. Sustainably maricultured fish, with Fish-In:Fish-Out (FIFO) ratios approaching 1:1, are up to 60 times more efficient in use of limited marine resources such as Peruvian anchovies than commercial fisheries targeting the top of the wild food chain. Expansion of open ocean mariculture should be viewed in a global context for integrated marine resource management, where governments should increasingly expand marine protected areas and apply individual fishing quotas and other regimes to restrict commercial overfishing.

Fulfilment of the promise of open ocean mariculture requires overcoming the existing anti-aquaculture activism. Governments must improve the legislative and regulatory frameworks for growth. There is a need to increase the scale and efficiency of offshore operations, by developing larger net pens with more robust netting materials, reducing reliance on divers and increasing automation for routine tasks. Industry is the best vehicle for driving these innovations, but governments can actively encourage investment through enabling legislation.

THE IMPERATIVES

There are numerous sound arguments for fostering the responsible, rational expansion of open ocean mariculture, such as: reducing user group conflicts in nearshore waters; stimulation of economic development; maintaining the viability of coastal communities; and finding alternative employment opportunities for displaced fishers. However, there are, first and foremost, two powerful drivers that unequivocally compel the expedient development of open ocean mariculture: (1) there is an urgent need to reduce commercial fishing pressure on the oceans, while at the same time there is a (2) pressing need to increase the availability of seafood for better human health and nutrition. Expanding open ocean mariculture is the only means of accomplishing both of these goals simultaneously. There is no practical alternative. Any argument against the expansion of mariculture into the open oceans therefore must be seen as arguing for either: (a) continued, unrelenting commercial fishing pressure; or (b) reduced seafood consumption, with consequent impacts on human health and survivorship. The precautionary principle is often touted as reason for inaction in development of new technologies. Clearly in this case, however, the costs of inaction are significant.

The environmental imperative: reducing the pressure on ocean resources

The demand for seafood continues to increase, with growing affluence in developing countries, and with broader recognition of the health benefits of increased seafood consumption. Yet almost all capture fisheries around the world are either fully fished or overfished. In the United States of America, closures or buyback schemes to reduce effort have effectively shut down once-productive fisheries for Atlantic tunas and swordfish, the groundfish of Georges Bank and other Northeast fisheries, Pacific Coast anchovies, albacore, and more recently, rockfish. Other environmental concerns for endangered species or marine mammals have seen closures or limitations placed on fisheries for shrimp in the Gulf of Mexico, purse seining for tuna in the Pacific, and longlining for tuna and swordfish in Hawaii and the US Pacific. Domestic fisheries production in the United States of America is currently sustained, in the main, by massive harvests of pollock in the Bering Sea – a former trash fish that is now used as a surimi component. In 1999, for the first time ever, the US imported more seafood than was caught by US fishers domestically. The seafood component of the US trade deficit currently runs around US$9 billion, and is increasing annually at around 12 percent.

The global fisheries crisis can be underscored by three examples: the increasing threat of extinction from overfishing and the failed Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) listing of Mediterranean and Eastern Atlantic stocks of bluefin tuna (*Thunnus thynnus*); the failure to recover – or the exceedingly slow recovery – of stocks of Western Atlantic cod (*Gaddus morrhua*) from overfishing despite almost complete cessation of trawling since around 1990; and the increasing acts of piracy off East Africa by former local Somali fishers who complain that they have no alternative employment since the decimation of their fisheries by foreign trawlers. These examples starkly reflect the biological and economic consequences of overfishing.

The public health imperative: Increasing protein and reducing heart disease

At the same time, there is increasing awareness of the importance that seafood consumption plays in a healthy diet. The definitive meta-study by Mozaffarian and Rimm (2006) found that a modest increase in seafood consumption in the United States of America, to two meals of oily fish per week, would result in a 35 percent reduction in deaths from heart disease and stroke, and a 17 percent reduction in overall mortality. A study by the US Food and Drug Administration (2009) supports these conclusions, noting that a 50 percent increase in seafood consumption nationally would save somewhere between 13 000 and 19 000 lives per year.

THE KONA BLUE OPERATIONS

The origins of offshore aquaculture in Hawaii

Prior to European contact, Hawaiians practiced extensive aquaculture in “loko” or fish ponds. These were inlets, bays, or shallow areas of reefs that the Hawaiians walled off from the ocean, and where ingress and egress of water was controlled by gates. Larvae recruited to the ponds were retained by the gates, and allowed to grow to harvest size on the pond’s natural productivity, or were fed with additional vegetable matter. Many of these ponds fell into disuse after Western contact and with increased sedimentation from agricultural run-off. However, the cultural tradition provided ready receptiveness to development of other forms of aquaculture in the islands.

Up until 1998, Hawaii’s ocean leasing legislation restricted any potential project to a maximum of 4 acres (approx. 1.6 hectares), and required that the project be limited to either educational or research purposes, but not commercial gain. Through several years of work by industry aspirants, and strong leadership by the State Aquaculture Development Program, legislation was passed into law in 1998 that allowed commercial aquaculture or energy projects in State offshore waters.

Permitting for the Kona Blue Farm site

Kona Blue Water Farms principals had been involved through the legislative review, and with passage of the bill, began research into developing hatchery culture techniques for high-value marine fish, and simultaneously surveying the Kona coastline (on the western, lee of the Big Island of Hawaii (Figures 1 and 2) for prospective offshore farm sites. After an extensive 3-year process of consultation and consensus-building with the community, Kona Blue was granted the requisite State and Federal permits for the original offshore farm site in March 2004.

FIGURE 1
Location of the Kona Coast on the western side of the Big Island of Hawaii affords moderate protection from trade winds and winter swells

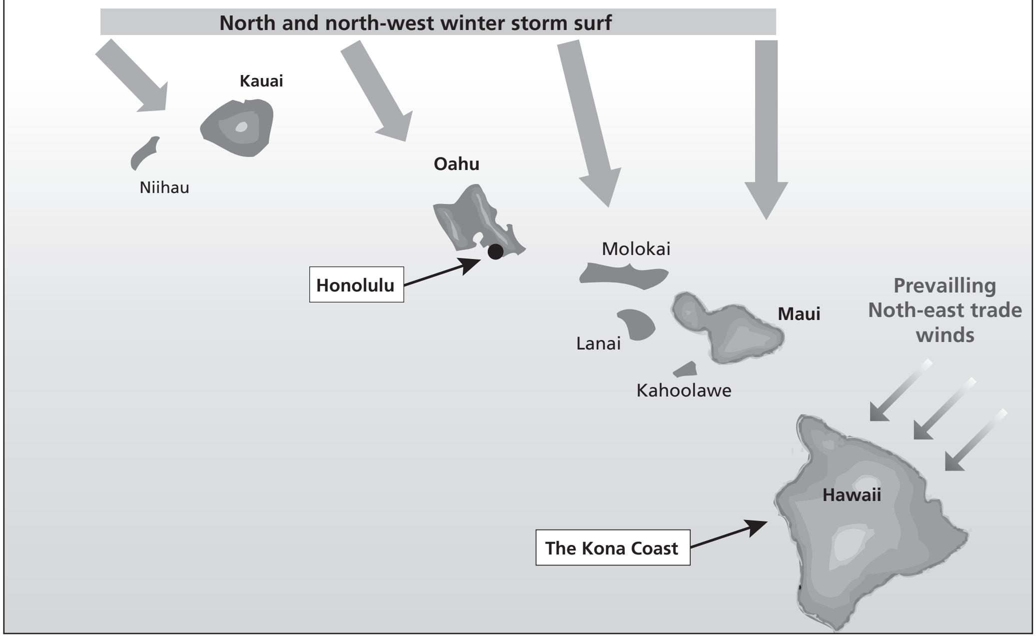
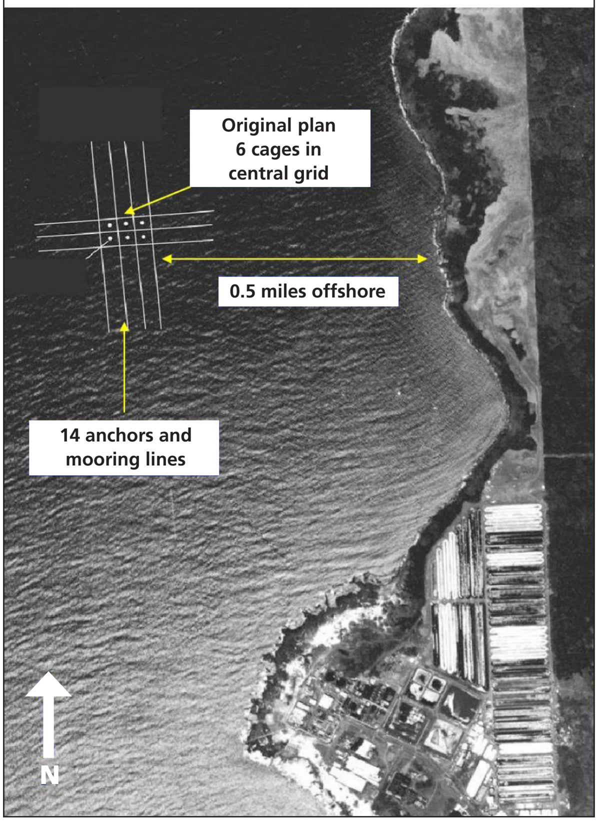


FIGURE 2
Kona Blue Water Farms' site located in waters over 200 ft (approx. 61 m) deep over a sand bottom, a half-mile (approx. 0.8 km) offshore from a pristine coral fringing reef abutting lava cliffs. The site is a mile north (approx. 1.6 km) of Keahole Point, and west of the Kona International Airport



The permitting procedures followed Hawaii's modified laws (Chapter 190 D, HRS, as amended), and other relevant laws. Regulatory requirements include permits and concurrence with a number of Federal, State and County regulations.

Federal

U.S. Department of the Army Permit

The Rivers and Harbors Act, Section 10, requires that a Department of the Army (DA) permit be issued for any activity that obstructs or alters navigable waters of the US Approval was therefore required for deployment of net pens, a feed barge and moorings. The U.S. Army Corps of Engineers (ACOE) is responsible for administering and granting DA permits. The criteria for issuance of a modified DA permit are similar to those for issuance of an environmental assesment (EA), but the DA permit also reviews compliance with all other Federal regulations. At the discretion of the ACOE, the modified DA permit can be processed and issued concurrently with other permits.

State

Conservation District Use Application

The Conservation District Use Application (CDUA) process is managed by the Land Division of the Department of Land and

Natural Resources (DLNR), who issue permits for any use of lands in the State Conservation District (under Chapter 183C HRS and HAR 13-5). This involves an environmental assessment (EA) or an environmental impact assessment (EIA) if there is a finding of significant impact (FOSI) or if there is "significant public controversy". The EA process is relatively simple and Kona Blue has conducted their own EAs for this project. There is no mandated requirement for an environmental impact study (EIS).

The decision to accept or reject the EA is made by the Land Board, who may then proceed to issue the lease and the permit. The decision is based on departmental review and public comment on the EA, and the recommendations of staff (usually the Office of Conservation and Coastal Lands – OCCL). A public hearing is required, and the Land Board hearing where a decision is made also allows for public testimony. Under the laws of the State of Hawaii, the Land Board must make a determination on a CDUA within 180 days of the application being accepted as complete, or else the permit is automatically granted. This avoids bureaucratic stonewalling, and assures an applicant of an expedient process.

A conservation district use permit (CDUP) is in perpetuity, but the lease has a maximum duration of 20 years. The chairman of the Land Board retains the right to modify, amend or withdraw the permit for breach of any of the conditions. The conditions specified by the State are usually extensive, and include monitoring and reporting provisions for a range of parameters.

National Pollutant Discharge Elimination System Permit

The State Department of Health Clean Water Branch (DOH-CWB), under the oversight of the Federal Environmental Protection Agency (EPA), requires a National Pollutant Discharge Elimination System (NPDES) Permit and Zone of Mixing Permit (ZOM) under the Federal Clean Water Act, Section 402, HAR 11–55. This applies specifically to discharges of point sources of pollutants into surface waters of the US from any fish farm operation that contains more than 100 000 lbs (approx. 45 mt) of biomass at any point. All aquaculture projects – including offshore net pen culture – are considered point-sources. The NPDES is valid for five years, and specifies allowable limits of 'pollutants', and monitoring requirements. The permit is issued or rejected after publication of a notice and a public comment period.

Coastal Zone Management Permit

Federal and State laws require that any project within the "coastal zone" requires a Coastal Zone Management Permit, issued by the Coastal Zone Management (CZM) Division of the Office of State Planning, to ensure compliance with all Federal, State and County laws and regulations. The issuance of this permit generally flows from the CDUP, but still offers a public comment period.

Aquaculture License

An Aquaculture Licence is required for commercial culture of a State regulated species under Chapter 187A-3.5 HRS and Sections 13–74–43 and 13–74–44 HAR. The DLNR Division of Aquatic Resources and the Department of Agriculture/Aquaculture Development Program (DOA/ADP) are the coordinating agencies.

Meetings and community consultations

For a finding of no significant impact (FONSI), an EA requires that project proponents have consulted with the community and other stakeholders. Kona Blue's principals spent extended periods of time discussing the company's aspirations for the offshore operation in a series of informational, briefing and consultative meetings with the community and Federal and State bureaucrats for the initial permit application, and then for subsequent permit modifications. Consultations with the community included "kupuna" (traditional Hawaiian leaders) and other native Hawaiian organizations (Office of Hawaiian Affairs, and Royal Order of Kamehameha), conservation interests (Sierra Club, Surfrider Foundation, and the West Hawaii Fisheries Management Council), and community groups (service clubs such as Rotary and Lions).

Subsequent requests for permit expansion and modification

The permits, regulatory issues and consultations required for Kona Blue's original permit application needed to be repeated to varying extents for each subsequent modification to the farm structures or operations. These permits were almost invariably granted, but the extensive time required for community consultation and permit application and approval for modifications – such as changes to the size and form of the net pens with no actual change in the production capacity – was a significant impediment to adaptive farm management, and a discouragement for investment. An application for doubling the size of the net pen capacity and the production volumes from the farm had included extensive, iterative scoping meetings with a range of state and federal agencies, and the public. There were few concerns raised against the requested expansion, but two "contested cases" were filed contesting the issuance of the EA: one complaint asserted that there was inadequate environmental information to justify approval, and one claimed that the permit contravened Hawaiian cultural prerogatives and rights. Although Kona Blue considered these complaints frivolous, a decision was made by the Kona Blue Board to withdraw the application 'without prejudice', and to seek farm expansion opportunities elsewhere (e.g. Latin America), where governments and the public were more receptive to industry development.

The offshore farm site and farm operations

Kona Blue began deployment of the moorings and net pens in February 2005, and first fish were harvested from the offshore site in September, 2005. Since then, production has grown to where the company has been harvesting up to 25 000 lbs (approx. 11 340 kg) per week of the company's sashimi-grade, trademarked Kona Kampachi®, peaking at around 500 tonnes per year in 2008. Kona Kampachi® (*Seriola rivoliana*) is also known as "kahala", longfin or highfin amberjack or Almaco jack. The species is related to the Japanese hamachi (*S. quinqueradiata*), but is native to Hawaii (USA) and is distributed throughout the warm waters of the world.

The lease area

Site selection is a critical component for any mariculture operation, but is particularly so for an innovative offshore farm that is pioneering both a new permitting process, and a new net pen system. The original farm lease site was selected using the following criteria:

- The selected site was in a deep water area, over 200 feet (approx. 61 m) deep, with brisk currents.
- There was little or no public use of this area. The farm site lies between the limits of normal recreational SCUBA diving (around 120 feet; approx. 36 m) and the normal depths for offshore trolling for "ono" (wahoo, *Acanthocybium solandri*).
- The site afforded some protection from both Kona storms and the strong trade winds. The proximity to shore also allows for future telemetry links to shore for farm control and security.
- There was ready access from Honokohau Harbor, five miles (approx. 8 km) to the south, which provides support facilities such as slips, fueling, and land for staging of equipment and feed.

- The site was directly offshore from the Kona International Airport and the Natural Energy Laboratory of Hawaii Authority (NELHA), and as such its use was consistent with the adjacent land uses and it represented no significant impact on the viewplane.

The farm site's bathymetry and oceanography are distinguished by the depth of water; the bare sand substrate; the strong currents through the area; the exposure to high winter surf and strong trade winds; and the adjacent shoreline of a narrow coral bench reef with a steep basalt (lava) cliff. A few black sand beaches also lie along the coastline, to the north of the site, but these are little used, except by recreational fishers. The pre-existing uses of the proposed farm lease area itself were negligible, because of its depth, the paucity of fish, and the barren benthos.

The 90 acre (approx. 36 hectares) lease area initially accommodated eight submersible Sea Station net pens, each of around 3 000 m^3 capacity. The outermost area of the lease is used almost solely for mooring lines, which require a 5:1 scope. The net pens were originally tied into submerged grids that are anchored into the soft substrate using steel embedment anchors and chains. A series of buoys and weights ensure that the anchor lines are perpetually taut, to eliminate any risk of entanglement by marine mammals. Bridles from the mooring grid corners attach to the net pen rims, to hold the net pens in place in each grid square.

The net pens are all concentrated towards the center of the lease area (see Figures 2 and 3), within two mooring arrays: one containing six net pens, and the other containing two net pens and the feed barge. The closest distance from the edge of the central grid array to shore is approximately 2 600 ft (approx. 792 m) or almost half a mile (approx. 0.8 km) to the northeast, to Unualoha Point.

The farm site lease provides "negotiated exclusivity": Transit, trolling, hoop-net fishing and hook-and-line fishing are permitted throughout the lease area, but for liability, insurance and safety reasons there is no authorized anchoring, SCUBA diving or swimming permitted.

Farm operations

The daily activities on the farm primarily consist of feeding the fish in the pens. Underwater video cameras inside the net pens are used to relay visual images to the operators on the feed barge. This enables the feed operators to regulate feed to ensure that no feed is wasted, and that excess feed does not fall below the net pen.

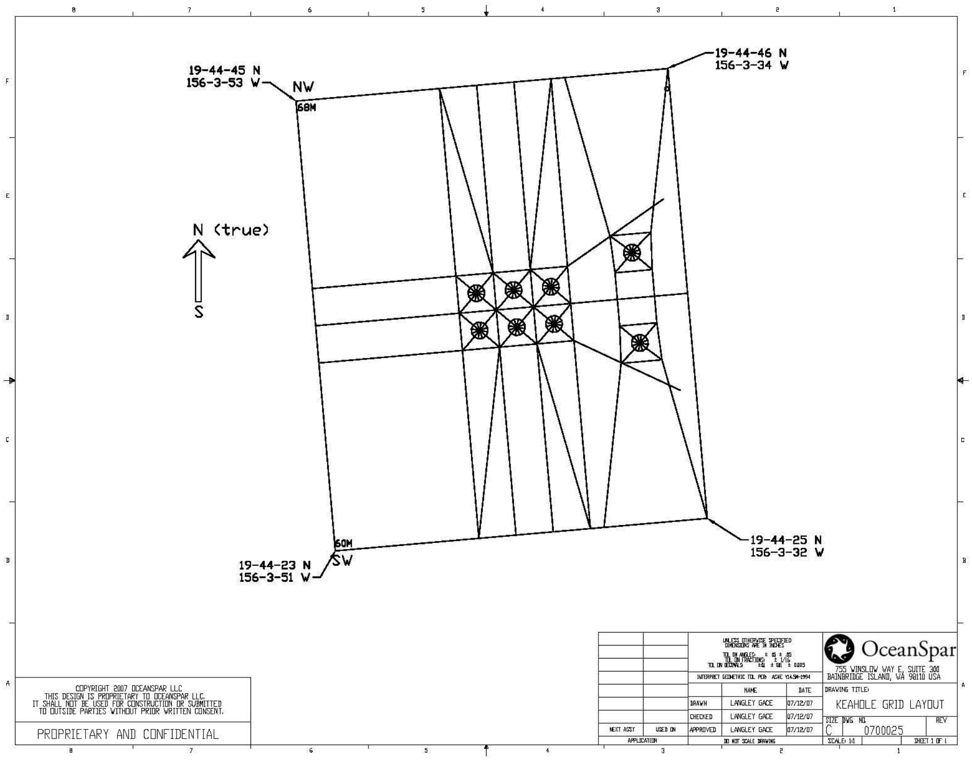
Any fish carcasses are regularly removed by divers. With the submersible net pens, divers must first raise the net pen to the surface (for safety reasons, to provide an air-space inside the pen), then enter and leave through a zipper. Carcasses are disposed of as solid wastes in the county land-fill.

Harvests usually occur twice each week. Fish are harvested into an ice-brine slurry, to quickly and humanely kill the animals with a minimum of damage. Fish are all transported whole, in ice-brine, to a single land-based processing facility, for packing and shipping. No fish processing occurs at sea during the harvests. Disposal of processing wastes is the responsibility of the wholesalers or other purchasers of the fish, but at present most trimmings from fillets go into the land-fill.

Support activities for the existing operation are based out of Honokohau Harbor, where a half acre (approx. 0.2 hectares) of land rented from the State accommodates containers for feed storage, gear storage areas, a closed workshop area, restroom and office.

The farm is also serviced by a semi-permanent feed barge/security platform vessel, which has been deployed on-site since October 2007. A separate harvest boat – the 74 ft (approx. 22 m) F.V. Kona Kampachi - transports harvested product back from the farm site to the harbor. Several other smaller work boats are also used to support net pen and grid maintenance and cleaning, and other tasks.

FIGURE 3
Original mooring array and grid dimensions – Plan view
The number of net pens is presently being reduced from current eight smaller pens to five larger pens, with the same overall culture capacity (24 000 m^3). The submerged central grid remains at around 30 ft (approx. 9 m) beneath the surface



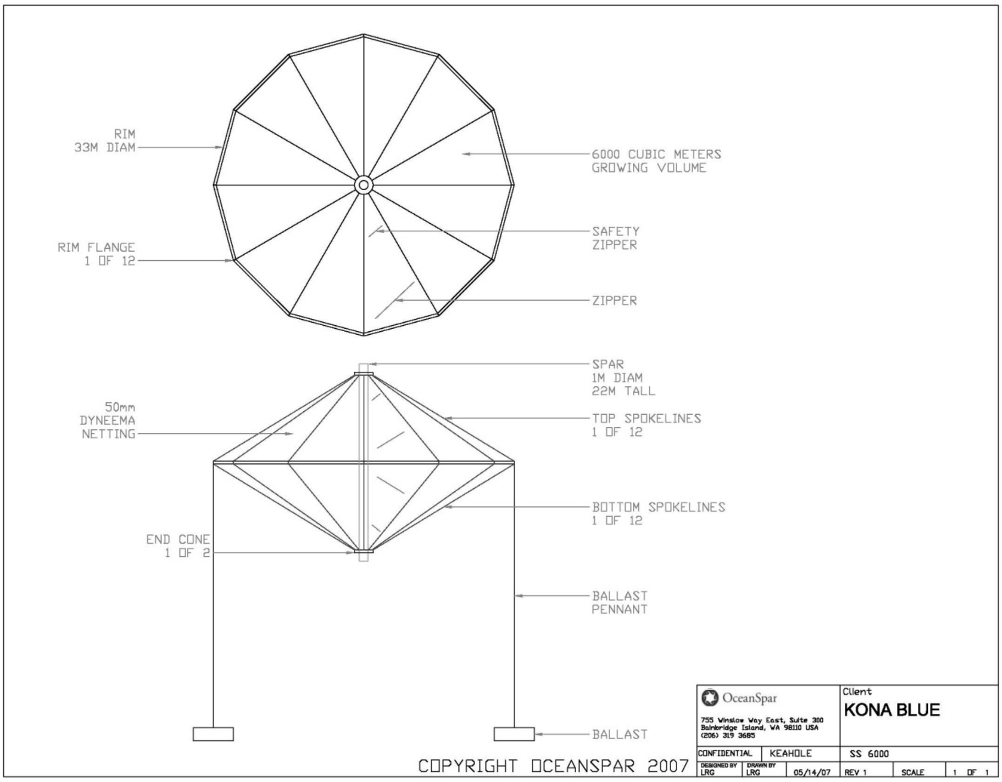
Marketing and Sales

The target market for Kona Kampachi® was the United States of America. Japan had considerable domestic production of hamachi (the traditional yellowtail, *Seriola quinqueradiata*) and local kampachi (primarily *S. dumerili,* but also some wild-caught *S. rivoliana*), and was already exporting the former to the United States of America. Japan also has a complex and costly seafood distribution system, a preference for Japanese-grown products, little interest in carrying a branded fresh seafood, and a tariff on imported seafood that competes with the domestic market. The European Union (EU) was not considered as a market because of the distance to airfreight the fish, and the prohibition against use of genetically modified organisms (GMO) feedstuffs and terrestrial animal by-products in fish feeds.

As this was a new product to the American market, Kona Blue undertook an extensive marketing campaign to introduce Kona Kampachi® to chefs, seafood distributors and the press to publicize both the fish itself, and the open ocean mariculture origins. The response suggested that there is indeed receptiveness among consumers to the Kona Kampachi® brand messages of sustainability, purity and healthfulness. Chefs also particularly liked the consistent availability and freshness of the fish: the company harvested product twice a week, and only enough to fill orders. Food writers and other journalists visited the farm site frequently. The company also sent product samples to chefs and distributors on request, and undertook a menu rebate programme of cash payments to encourage chefs to carry the fish by the brand-name on their menus.

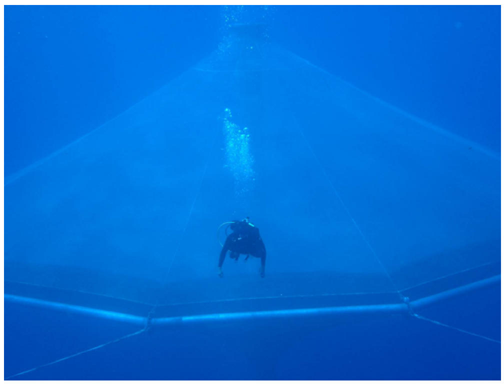
Kona Blue also engaged in active outreach to environmental non-governmental organizations (NGOs) with particular interest in seafood sustainability, and became actively involved in legal issues – such as the ongoing attempts to pass legislation to

FIGURE 4
Submersible Sea Station® Net Pens deployed on Kona Blue farm site



a) Design of submersible SS6200 Sea Station net pens with central steel spar and steel rim.

b) Sea Station SS3000 raised to rim-level on the Kona Blue farm site.



c) A submerged Sea Station SS3000 and diver on Kona Blue site.

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open up the US Exclusive Economic Zone (EEZ) to mariculture, and for development of organic standards for seafood in the US – and in the process of developing sustainability standards for certifying individual farms, through the World Wildlife Fund (WWF) dialog process for *Seriola* and cobia (the *Seriola* and Cobia Aquaculture Dialogue – SCAD).

By mid-2008, Kona Blue was selling approximately 25 000 lbs (approx. 11 340 kg) per week of whole fish into the US market. The vast majority of this was being airfreighted to the mainland (the fish is always sold fresh), with about 50 percent sold on the West Coast, 35 percent sold on the East Coast, and 15 percent sold in Hawaii. The product was carried in both high-end sushi establishments and white table-cloth restaurants, but was still usually served in the latter as a raw appetizer – a sashimi, crudo (i.e. raw), poke ("ceviche") or carpaccio. The high fat content of the fish also makes it highly amenable to cooking. Retail sales volume has not been significant, but with growing brand awareness, this sector of the market is expected to grow.

Production decreased through 2009 and 2010 as the company prepared to reconfigure the offshore net pen array, and to change to fewer, larger Sea Station® cages. This work is presently under way, and sales are again expected to reach 25 000 lbs (approx. 11 300 kg) per week by the end of 2010.

THE IMPACTS

The presumed problems

Aquaculture – or indeed, development of any food production system – brings with it attendant environmental concerns. Fish farms are widely accused of environmental degradation. The concerns that are often voiced include:

- potential for detrimental impacts on water quality;
- potential for nutrient enrichment of the substrate beneath the farm;
- potential for antifoulant paints from net pens to contaminate the substrate;
- potential for therapeutant or antibiotic misuse to harm the surrounding biota;
- potential for escapes to outcompete wild fish for spawning grounds or feed;
- potential for escapes to dilute the wild fish gene pool or establish themselves as alien species;
- potential for proliferation of pests, parasites and diseases inside the net pens, which can then be transferred to wild fish;
- potential for entanglement of whales, dolphins and other marine mammals;
- potential for disruption of marine mammal or other species' migratory paths;
- potential for harmful deterrents or fatal control measures against predators;
- potential for excessive use of fishmeal and fish oil, leading to overharvesting of the smaller pelagic species targeted by industrial reduction fisheries;
- potential for exclusion of other user groups from traditional, cultural or recreational uses of the farm area; and
- potential for visual impact on the viewplane from the net pens.

The potential for any or all of these environmental impacts was used by a small minority to oppose the original Kona Blue farm permit and lease, and subsequent requests for expansion or modifications to the farm site. Opponents against open ocean mariculture also frequently raise some or all of these issues as cautions against any imprudent expansion of the industry, or as reason to oppose any Federal legislation that would allow open ocean fish farming in the US EEZ (i.e. from the State waters boundary at three miles or 12 miles offshore [approx. 4.8 and 19 km, respectively] out to 200 miles [approx. 322 km] offshore).

With almost five years' experience at the Kona Blue farm site, then, it is appropriate to evaluate the actual data and observations recorded at the Kona operation, and to compare this experience with the concerns that are so frequently voiced. Each of these issues is therefore examined in detail, below, beginning with an evaluation of the *de novo* environmental status of the Kona Blue farm site, and then detailing the impacts that have occurred, their context, and their significance.

The actual observed impacts: locally

Water quality and effluent impacts

The water quality at the farm site is close to oceanic, with strong currents and low turbidity. Underwater visibility usually exceeds 100 feet (approx. 30 m) or more.

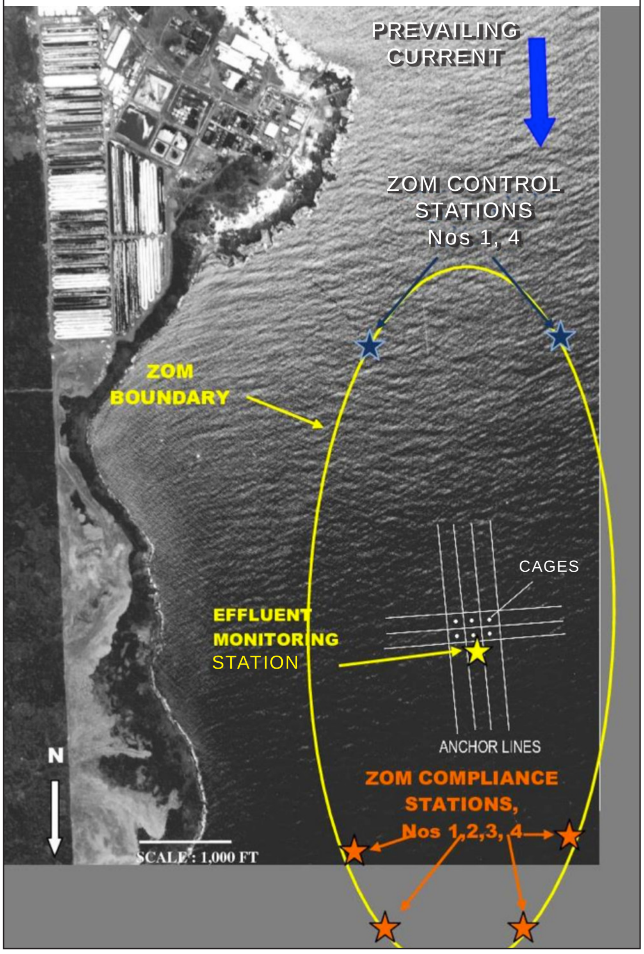
General water movement patterns at the farm site are governed by the longshore currents past Keahole Point (the western-most point of the Big Island of Hawaii), one mile (approx. 0.8 km) to the south. An S4 current meter deployed at the farm site over several periods since 2004 showed regular peak current speeds of over 50 cm/sec (about 1 knot at a depth of around 40 ft or 12 m). Current headings were either generally to the north (predominantly) or to the south. The two points of first impact downstream from the farm site are therefore either Keahole Point, around one mile (approx. 0.8 km) to the south of the site, or the Mahai'ula-Makalawena shelf area, around three miles (approx. 4.8 km) to the north.

Because of the community concerns about potential impacts from the farm operation on water quality, the company had made commitments during the permit process to ongoing transparency and objectivity in monitoring. These commitments included:

- use of objective, third party experts to collect the water quality samples;
- use of local water quality laboratories – such as NELHA Water Quality Lab, or local private laboratories – for conducting the sample analysis;
- place copies of all monthly water quality monitoring at local repositories, such as the State Aquatic Resources office at Honokohau, or the NELHA library, so that local residents can review this data; and
- provide reasonable access to Federal, State and County officials for monitoring and oversight purposes.

FIGURE 5
Water quality sampling station map

Aerial photograph of the Kona Blue site showing water quality monitoring sampling station locations. Sampling stations under a prevailing N-setting current are shown. Under a S-setting current, control and compliance stations will be reversed. ZOM = Zone of Mixing



Monthly measures are taken of ammonia and turbidity (the two most relevant water quality parameters for fish farming) at three depths (surface, mid-water – 50 ft. [approx. 15 m] deep, level with the submerged net pens, and at the bottom) and at a total of seven stations (two control stations up-current, one effluent station immediately down-current of the net pen with the greatest biomass, and four ZOM stations 4 000 ft. [approx. 1220 m] down-current; Figure 5). Quarterly measurements are also taken for a range of other parameters.

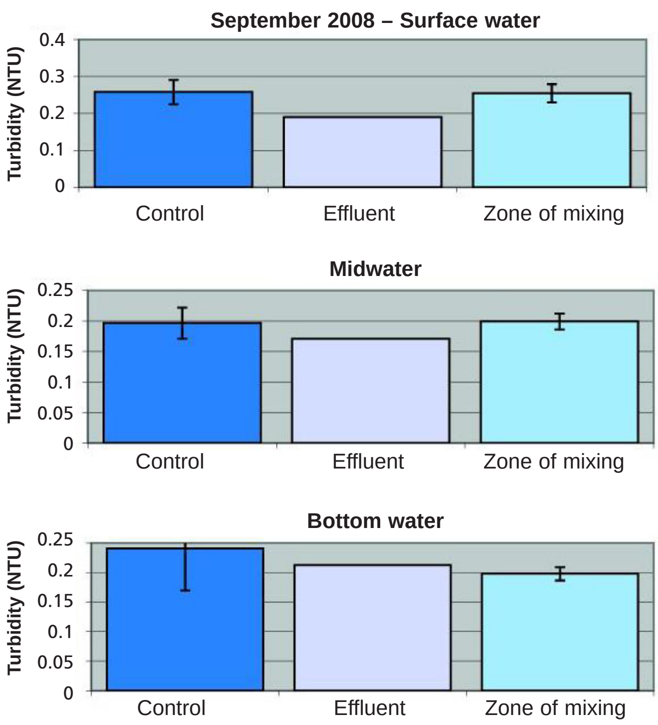
Figure 6 shows means for each sample site for turbidity for September 2008, when the farm was at peak production of around 500 tonnes annually. Turbidity is probably the best metric for fish faeces and other particulates in the water, and so is most likely to reflect any impact from the farm's presence. These data are definitively clear – there is no discernible difference between water quality parameters at the up-current control sites, and the effluent site (1 m down-current of the netpen with the highest biomass) or the "zone of mixing" (ZOM) sites down-current. These results confirm that *there is no measureable impact* on water quality from the existing farm operations.

Benthic impacts

The substrate beneath the farm is over 200 ft (approx. 60 m) deep, and is almost exclusively comprised of bare, coarse sand. Located along the shoreline, some 2 000 ft (approx. 609 m) to the east (directly across the longshore currents) is a diverse coral reef community.

FIGURE 6

Typical turbidity data from monthly sampling around the Kona Blue farm site. There is no discernible difference in water quality between the two control sites (up-current), one effluent site (immediately down-current) and four zone of mixing sites (4 000 ft or 1 220 m down-current) of the farm site



Impacts on substrate beneath and around the farm site

Prior to farm installation, a preliminary survey of the site was undertaken by repeated bounce dives, using SCUBA, to depths of 220 ft (approx. 67 m). Because the depth of the farm site is beyond the limits of normal safe diving, and the strength and unpredictability of the currents precluded ready use of grab samples or drop video-cameras, the original permit provided that no benthic monitoring would be required. Over time, however, permit requirements were tightened to include grab sample monitoring of substrate chemistry and infaunal micro-mollusc community structure, and video monitoring using drop cameras.

These results generally indicate that there has been no measureable impact on the benthic community around the farm site. There have been episodic perturbances of substrate chemistry immediately underneath the cage footprint, with a few instances of anoxic conditions during 2007, during periods when a new feed distribution system was being tested. This resulted in some pulverization of pellets and reduction of feed to a "slurry" rather than discrete pellets. Once the feed system was refined, the substrate returned to its more normal condition, there was no further significant nutrient enrichment of the substrate.

Filamentous algae have also been visible in the drop-camera videos from around the farm site. These appear to have been detached from the cage mesh or the mooring lines, as the algae are not attached to the coarse sand substrate. Presumably these algae are dispersed during periods of high current.

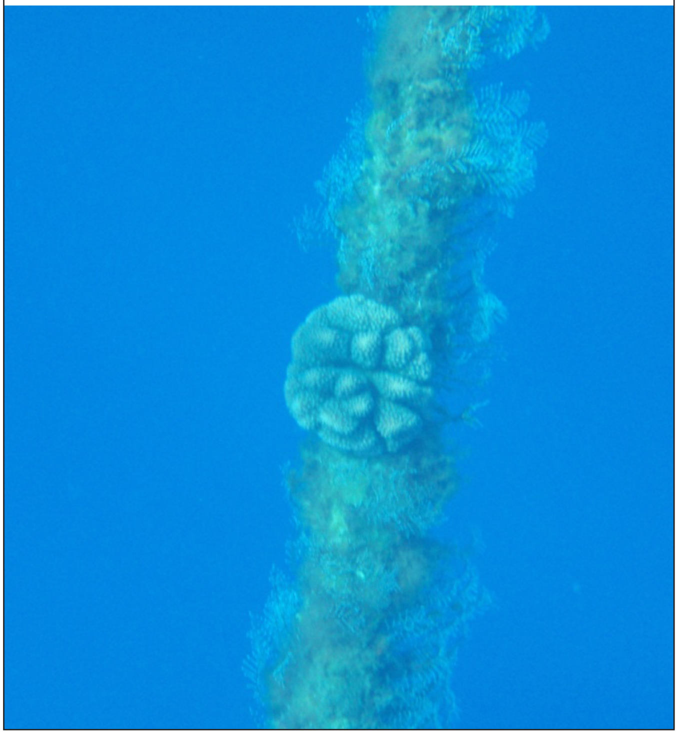
Monitoring of infaunal micro-mollusc assemblages in the substrate samples has also demonstrated that there has been no significant change in the community structure resulting from the farm presence.

Impacts on the adjacent coral reef community

A comprehensive survey of marine biota was conducted on the reef directly adjacent to the existing farm lease area, just south of Unualoha Point. The survey of the benthic biota of the fringing reef crest used protocols identical to those employed by the Hawaii Division of Aquatic Resources (DAR) West Hawaii Reef Management Task Force Survey. This provided an extensive set of "control" sites: the other benthic and fish data from the sites along the 90 miles (approx. 145 km) of coastline on West Hawaii. A series of four transects of 25 × 2 m extended parallel to the reef crest, immediately shoreward of the seaward edge of the reef. Video footage was made of these transects, and digitized for selection of random points on the video frames.

The Makako Bay – Unualoha site has been repeatedly resurveyed since the original 2003 survey. Although no formal reports have been compiled, there have been no significant changes in benthic community composition or fish populations, according to Dr William Walsh, of the State's Division of Aquatic Resources (personal communication, 2010).

FIGURE 7
A *Pocillopora damicornis* coral colony on a mooring grid line around the Kona Blue net pens (within about 15 m of net pen stocked with fish). The presence of coral colonies that are highly sensitive to nutrient enrichment on moorings and buoys confirms that the operation has no significant impact on marine biota in the area.



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Biofouling on the farm structures

There is also profuse growth of macro-invertebrate biofouling on the grid-lines and buoys of the mooring array, as well as on the bridle lines that attach the cages to the grid, and the rims of the cages themselves (Figure 7). This fouling includes diverse macroalgae, bivalves (several species of mussels and oysters: *Pteria* sp. and *Pinctada* spp.), corals (primarily *Pocillopora* and *Porites*), sea urchins (primarily *Echinothrix calamaris*) nudibranchs (*Stylocheilus longicauda*) and sponges. These all settle out of the plankton onto the farm structures, and their presence does not represent any significant or even measureable reduction in the available recruits to the nearby coral reef area. The growth of the corals, particularly, is compelling evidence that the presence of the fish farm operation is not deleterious to benthic organisms.

Apart from the one brief instance of anoxic conditions beneath the net pens, then, there have been no other adverse impacts on benthic communities in, underneath or around the net pen area.

Pests, parasites and pathogens

Kona Blue employs an integrated pest management strategy to optimize fish health, reduce interactions or minimize impacts on wild fish stocks, and reduce any potential environmental impacts from therapeutant use. Any therapeutant use is conducted under the oversight of US Fish and Wildlife Service (USFWS), and Food and Drug Administration (FDA), with State oversight through Office of Conservation and Coastal Lands (within Department of Land and Natural Resources) and Clean Water Branch (CWB – within the Department of Health). Federal Environmental Protection Agency (EPA) has oversight through the NPDES (National Pollutant Discharge Elimination System), which is administered by CWB.

As with most farmed animals, *Seriola rivoliana* is subjected to small external pests – in this case, the skin fluke, *Neobenedenia* sp. – that attach themselves to the skin of the fish. These flukes do not pose any risk to human health, and do not themselves detract from the quality of the harvested product, but may cause irritation to the fish. If left unchecked, the flukes can become a health problem for the animal, as the fish rub themselves on the netting to ease the irritation. Kona Blue uses occasional treatments of dilute hydrogen peroxide solution (at effective dosage rates of 200–300 ppm) to control levels of skin flukes among the fish in the net pens. Hydrogen peroxide (H_2O_2) breaks down very rapidly in sunlight to form oxygen and water. Hydrogen peroxide is also considered an acceptable organic aquaculture treatment under the draft USDA organic aquaculture guidelines, and USDA organic agriculture standards.

Under the permits in place at the existing site, such therapeutant use must demonstrate that there is no risk to the fish under treatment, or to the environment or human health. Monitoring of the effluent from any bath treatment at 100 percent concentration is mandated under the "Whole Effluent Toxicity" (WET test) section of the NPDES permit. Results to date from the existing farm operation suggest that there are no significant environmental impacts from the use of the hydrogen peroxide. Ongoing effluent monitoring for WET test bioassays using larval fish (Pacific topsmelt, *Atherinops affinis*; conducted by Nautilus Laboratories in San Diego, California, United States of America) confirm that there is no significant difference in the rates of larval fish survival between control samples taken 4 000 ft. (approx. 1 219 m) up-current of the net pen, and samples taken of the whole effluent (100 percent concentration of the bath treatment water) at the conclusion of the bath treatments. There is therefore no mechanism for any measureable impact on the pelagic or benthic communities, or the surrounding water quality from the use of this therapeutant.

In addition, monitoring of wild kahala (*Seriola rivoliana*) stocks indicates that there is no significant proliferation of *Neobenedenia* sp. in the population around the farm area. Broodstock are regularly collected by commercial fishers from around the farm area, to replenish the wild stocks in Kona Blue's hatchery. These fish are usually taken along the "drop off" of the marlin fishing grounds, about one mile (approx. 0.8 km) to the South of the farm, and are sampled for ectoparasites upon capture by immersion in a freshwater dip. Although these fish are usually infested with a number of other ectoparasites, the prevalence of *Neobenedenia* sp. has never averaged much more than one individual per fish. By contrast, a parasitic copepod (sea lice, similar to *Caligus*) infests wild fish at average rates of around ten individuals per fish, and yet is not found at all on the farmed fish, and does not proliferate within the net pens.

A number of innovations, either in progress or planned, should also further reduce the proliferation of *Neobenedenia* sp. on fish inside the net pens. The farm is being re-configured to fewer, larger Sea Station net pens. With a planned reduction in the number of net pens, a reduction in the surface area-to-volume ratio of the remaining net pens (from double-cone net pens to a more cylindrical shape), the improved surface material characteristics and rigidity of the Kikkonet™ plastic monofilament net mesh (which make it easier to clean), and the improved access for offshore crew to regularly clean the nets from the surface (thereby breaking the skin fluke life-cycle by dislodging the adhesive eggs on the mesh), the proliferative tendencies of the skin fluke should be further reduced.

Kona Blue does not use prophylactic antibiotics, but has, under the same regulatory oversights described above, used Florfenicol® to treat *Streptococcus iniae* infections that sometimes afflict juvenile fish after the stresses of transfer offshore. These treatments last for only ten days, and are also accompanied by WET test water quality monitoring. These WET tests have repeatedly demonstrated no impact on marine biota from the therapeutant. A vaccine is available for other strains of *S. iniae*, and one specific for use in Hawaii is under development for future fingerling transfers, to thereby circumvent the need for Florfenicol. *S. iniae* infections are also not an issue with larger fish, once they have overcome the initial stress of transfer from the nursery to offshore.

Much of the concern over proliferative capacities for fish farm pests, parasites or pathogens is derived from conflicts between salmon farming and wild salmon runs. Some research – though disputed – suggests that sea lice from salmon farms is detrimental to survival rates of juvenile salmon as they migrate through fjords or river mouths to the sea. Most marine fish, however, are broadcast spawners. Juvenile marine fish are therefore dispersed over vast areas of ocean and reef, and do not usually have vulnerable migratory patterns. Given such a distinct difference in life-histories between salmonids and marine fish, there would seem to be limited applicability of the salmon and sea lice research, or the concerns with impacts on vulnerable life stages, to open ocean mariculture.

Interactions with wild fish

Kona Blue cultures only Kona Kampachi® (*Seriola rivoliana*), but the pertinent State permit also allows the company to possibly culture other amberjack (the other "kahala" species, *S. dumerili*), mahimahi (*Coryphaena hippurus*) and Pacific threadfin (*Polydactylus sexifilis*).

Aggregative effects on wild fish stocks

The existing operation does have an aggregative impact on some species of fish in the area, but this is considered neither deleterious nor significant. Fish are attracted to the site for a number of possible reasons: the fouling on the net pen, the occasional release of small quantities of uneaten food from the net pen during periods of strong currents, and the aggregative nature of objects in open water (as for fish aggregation devices). The make-up of the resident and transient fish communities around the net pens may vary over time.

Pelagic or larger demersal fish frequently occurring around the Kona farm site include mackerel scad ("'opelu", *Decapterus macarellus*), "ulua" (giant trevally, *Caranx ignobilis*), wild kahala (*Seriola rivoliana* and *S. dumerili*) and barracuda (*Sphyraena barracuda*). Occasionally, schools of rainbow runners ("kamanu", *Elegatis bipinnulatus*) and false albacore tuna ("kawakawa", *Euthynnus alletteratus*) move through the net pen area. Larger pelagic fish, such as yellowfin tuna ("ahi", *Thunnus alabacares*) and occasionally ono (wahoo, *Acanthocybium solandri*) are also attracted to the area by the baitfish, or by the net pens themselves.

A number of other, smaller fishes that are more normally associated with coral reefs settle out of the plankton and assume residence either around the subsurface buoys or around the cages themselves. Such residents include schools of Sargeant-majors (*Abudefduf abdominalis*), dascyllus (*Dascyllus albisella*), chromids (primarily *Chromis hanui* and *C. ovalis*) wrasses (primarily *Coris* spp. and *Thalassoma* spp.) and kyphosids (*Kyphosus* spp.). As these fish are settled from the plankton, their presence is not considered a significant detraction from the biomass or diversity of the fish fauna on the adjacent reef.

Escaped fish interaction with wild stocks

Concerns about potential negative impacts of escaped fish are often cited as one of the reasons for objections to fish farming. However, this issue is most pressing only where non-native fish are cultured in areas where escapes might become established or compete with local species, such as Atlantic salmon in the Pacific coast of Canada. Kona Kampachi®, by contrast, is native to the waters of Kona. In addition, Kona Blue recognizes that the innovative net pen engineering means that there is some possibility of escape incidents over the initial proving period, and development of refinements. In consideration of this, Kona Blue has deliberately not applied any selective breeding in the hatchery, and has not used any broodstock beyond F2 (i.e. all broodstock are either wild-caught, first or second generation captive-reared). There is therefore no mechanism for development of any significant difference in the genetic make-up of the fish inside the net pen from the fish in the wild. This reduces any potential impact from escapes to merely direct ecological impacts.

Furthermore, the concerns with the effects of fish farm escapees on wild fish genetics are again largely a consequence of the conflicts between salmon farming interests and wild salmon conservationists. Yet wild salmon stocks are unique, in that each river system or stream may have a genetically discrete stock from the adjacent watershed. Any blurring of this finer-scale differentiation, by inter-breeding between escaped salmon and wild stocks, could represent a loss of genetic diversity. Again, however, these concerns are not germane to farming of marine fish in the open ocean. As marine fish are broadcast spawners, there is only a coarse zoogeographic genetic granularity.

Tagging research demonstrates that *Seriola* and other carangids migrate frequently between islands in the Main Hawaiian Archipelago. One *Seriola* migrated from French Frigate Shoals, in the Northwestern Hawaiian Islands, to the Big Island – a distance of 678 miles (over 1 000 kilometres) over 3.6 years at liberty (Tagawa and Tam, 2006). The potential genetic impacts of Kona Kampachi® escapees on the wild stocks of *S. rivoliana* are therefore, minimal.

Those Kona Kampachi® that have escaped from the Kona Blue net pens – either through "leakage" as divers enter or leave the pen through a submerged zipper, or from breaches in the netting – are invariably subjected to very heavy predation pressure. Individual escapees survive outside of the zipper for usually less than a minute before being eaten by either the resident ulua, or by the bottlenose dolphins that are frequently in the area. The long-term prospects for survival and reproductive success of any escapees are therefore highly dubious. In addition, any escapes that do survive in the wild are presumably entering a wide-open ecological niche, due to the severe depletion of other deep water species – such as the deep water snappers – from commercial fishing. There is little likelihood of escapees competing in any significant manner with the few remaining wild snapper stocks.

Other wildlife interactions

Sharks

The single overarching feature of shark interaction with the offshore fish farm site has been – contrary to conventional wisdom and activist concerns prior to the farm deployment – the general absence of sharks around the net pens. For the first eight months of operation, only one fleeting shark sighting occurred: a small tiger shark ("mano", *Galeocerdo cuvier)*. There are generally brief influxes of tiger sharks to the area in the months of September and October of each year. Most of the animals appear individually, or in pairs, with a range of sizes from 8 to 15 ft. (approx. 2.4 to 4.6 m) in length, and generally seem to not take up residence on the farm site. Most tiger sharks only show interest in dead fish inside the net pens, and generally exhibit no interest in or aggression towards the farm workers.

In the first year of operation, however, before workable dive plans and efficient farm operations had evolved, the company divers were not able to keep the pens sufficiently clear of dead fish. Over about a six week period, in September and October of 2005, tiger shark sightings had become increasingly regular. One animal began to appear repeatedly, over consecutive days. This shark seemed to take up residence at the farm site, and began to exhibit more aggressive behaviour – on one occasion attacking an inert plastic float moored as a surface marker. The following day the shark chased a diver out of the water and onto a raised Sea Station™ net pen. At this point, farm managers decided that preventative action needed to be taken to assure the divers' safety, and the animal was humanely dispatched by a "bang-stick" (powerhead charge detonation) to the skull.

Recognizing the long-term unacceptability of such predator control measures, from a sustainability perspective, a cultural context, and a moral position, Kona Blue sought alternative means of addressing this issue. A shark management plan was developed in consultation with State Aquatic Resources personnel in Kona, which included a range of measured responses. Observations from research tagging trials had also shown that sharks which were caught, subdued, and implanted with a radio-marker tag usually vacated the area for an extended period. This, then, provides an acceptable, sustainable, non-terminal solution, if tiger sharks ever again become problematic at the site.

In subsequent years, tiger shark sightings usually increased in frequency at the farm site in the late-September early-October period. However, sharks were neither persistent, nor consistent. Farm operations had become more adept at removing dead fish, and the shark management plan allowed divers to continue to work safely. One animal or rarely two contemporaneously, may appear at the site, and remain for an hour or so, before moving away, presenting little inconvenience to farm operations, and no real risk to diver safety.

Kona Blue has also, in collaboration with the researchers of DAR and the Hawaii Institute of Marine Biology (HIMB), established a receiver station on the farm site, as part of the larger research program for tracking tiger shark movements along the West Hawaii coastline. The first data series obtained suggested that the observations by the farm work crews was correct - that tiger sharks only very infrequently pass by the site, and rarely do they show any interest in the operation. From July 2006 to May 2007, there were a total of eight records of tagged tiger sharks in the Kona Blue farm area. None of these sharks took up residence. One animal passed by the farm site three times in two months, another animal was recorded twice in two months, and three other animals had single records (Figure 8).

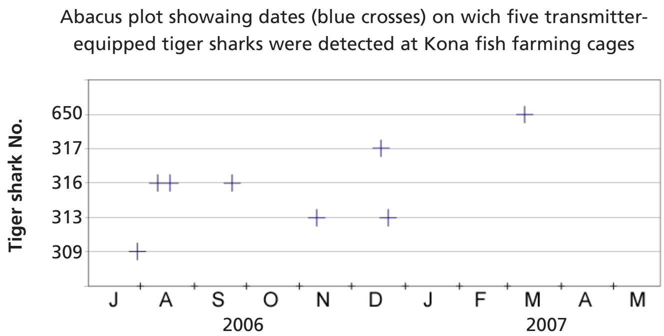
Over 2008 and 2009, however, further tiger shark tagging trials showed that two animals appeared to regularly return to the farm site over periods of up to five months. Two other sharks ranged over the entire Kona coast area, but for several weeks at a time were recorded exclusively from the farm site. All animals eventually moved on; one was later detected off Maui. While these results suggested that the farm site became a “waypoint” for the animals over a few months, the “long-term entrainment (e.g. years) of tiger sharks is unlikely” (C. Meyer, personal communication, 2010).

There have also been sightings of sandbar sharks (“mano”, *Carcharhinus plumbeus*) around the net pens. Initially, these were rare (none in the first year of operation), but since October 2006, the frequency of sightings and number of sandbars has increased. These animals are usually seen in small groups (one to four sharks), below the net pens at depths of over 100 ft. (approx. 30 m). They rarely rise up to the level of the net pens. Sandbar sharks are more secretive, and cannot readily be distinguished by any markings. No sandbar sharks were caught during the tagging trials in 2008–2009 (ibid). It is therefore, unclear if these are always the same individuals, or if they represent a larger population of animals that periodically move through the area.

In the period from June to August 2008 there were a series of breaches of varying sizes in the Dyneema® webbing of one net pen that corresponded to shark bites. The same net pen was also breached in August 2009 by a small Galapagos shark that entered the net pen. The Galapagos was captured and released alive by company divers, unharmed except for a small dorsal fin notch for later identification. In each instance, breaches were sealed immediately on discovery. These incidents underscore the vulnerability of even sturdy Dyneema® nylon mesh, and have led to a plan for wholesale installation of Kikkonet® rigid plastic webbing across the farm. This material has been used in *Seriola* culture in Japan for over 25 years, and has been successfully used in crocodile and shark-infested waters by a sea-cage barramundi farmer in North Queensland, Australia. Kona Blue therefore anticipates that the use of Kikkonet webbing will reduce mesh breaches to negligible levels, and significantly reduce escapes and the attractant nature of the escapes to the bottlenose dolphins and sharks.

FIGURE 8

Frequency of tagged tiger shark occurrence at Kona Blue farm site: 2006–2007. Five tagged sharks were recorded over an 11–month period, with the most frequently occurring shark being present three times over a two month period. No animals took up residence, or showed any strong site affinity.



Overall, the evidence from the Kona Blue site confirms that there are no significant negative impacts from any aggregating effects of the net pens on sharks. The evolution of a non-terminal, humane plan for managing sharks on the farm site underscores the importance of commercial experience to improve open ocean farming practices.

Turtles
The threatened green sea turtle (*Chelonia mydas*) is common in the nearshore waters of the main Hawaiian Islands. The endangered hawksbill turtle (*Eretmochelys imbricata*) is infrequently found in Hawaiian waters. The principal nesting site for the green turtle is in the Northwest Hawaiian Islands, on French Frigate Shoals (Balazs, 1980). No turtles have been observed in the area of the farm site, but it is possible that they occasionally transit through the site. If they were to do so, the taut-line mooring system and stiff-mesh net pens will prevent animals from becoming entangled.

Seabirds
The submerged net pens used by Kona Blue do not significantly impact seabird populations. The farm area itself is infrequently used as a foraging area by seabirds. Most seabird activity in the area is confined to the fishing “grounds” which extend to the northwest of Keahole Point.

Monk seals
There are four conceivable ways for open ocean fish farming to have a significant negative impact on rare, threatened or endangered wildlife, such as monk seals, dolphins or whales. The project may: (a) present a significant obstruction to natural migratory patterns; either (b) attract; or (c) repel the animals and thereby disrupt their normal behaviour; or (d) the animals may become entangled in the ropes of mesh of the net pens or moorings.

Monk seals have been observed at the existing farm operation on two occasions, both in association with escape incidents from the nylon mesh nets on the surface nursery pens that were previously in use at that site. (These nylon mesh surface net pens were removed in 2006, as Kikkonet was, at that time, not yet available outside of Japan). On each of these occasions, the monk seal was preying on the small, escaped Kona Kampachi™, but once the school was effectively eradicated by predators, the monk seals moved away. A radio tag allowed movement of one monk seal to be tracked from the Unualoha site one day, to a beach on Maui the following day, clearly affirming that the animal did not take up residence or become conditioned to the availability of escapees.

Dolphins
Makako Bay, almost a half mile (approx. 0.8 km) to the south of the farm site, is frequented by large schools of spinner dolphins (*Stenella longisrostris*), on nearly a daily basis. These animals usually follow a diurnal pattern of movement from the Makalawena shelf area to the north, along the reef edge to the shallow areas of Makako Bay, where they rest for some time during the middle of the day. Some concerns were expressed during preliminary hearings about the potential for the farm operation to interfere with the spinner dolphin patterns of movement or resting habits. There is no evidence to suggest that this has been the case. There have only been a few occasions over the five years of operation offshore when divers or workers on the farm site have witnessed spinner dolphins coming anywhere near the net pens. The net pens clearly do not impede the usual pattern of spinner dolphin movement towards Makako Bay, and nor do they affect the resting pattern of the dolphins.

Over the last three years, the existing farm operation has demonstrated a propensity to attract bottle-nose dolphins (*Tursiops truncatus*). No bottle-nose dolphins were previously present on the farm site, but the animals have begun to appear regularly at the site since about October 2006. Patterns of dolphin movement are best characterized as one or two animals, every day or so, with occasional instances of groups of up to seven or eight animals. There is no regularity to the animals' appearance on the farm site: they may be present all day or only in the morning or only in the afternoon.

Kona Blue staff monitor and report on dolphin activity to the Hawaiian Islands Humpback Whale National Marine Sanctuary (HIHWNMS) and NOAA's Pacific Islands Regional Office (PIRO) Public Relations Department (PRD). The bottlenose dolphins are probably attracted to the farm site by a combination of: (i) the presence of the midwater structures acting as a fish aggregating device (FAD) and the associated fish community that is present around the net pens; (ii) the occasional provisioning from "leakage" escapes when divers enter or exit a net pen, and from the rare larger escape incidents when predators have breached the Dyneema nylon webbing; and (iii) interaction with divers outside of the net pen, as the divers move about the farm from boat to net pen and back.

One individual dolphin has taken up residence over 2009 and 2010. This animal was suffering from a large fishing hook and leader line that had become lodged in its jaw, and it was present on the farm site almost continuously during this period. For many months, the dolphin was lethargic and lost weight, but more recently (as of late 2009) has appeared to be more active and in better condition (J. Viezbieke, personal communication, 2009). The aggregative effective of the net pens for this one animal might therefore be interpreted as beneficial.

No other individual bottlenose dolphin has taken up permanent residence at the farm site. There are no other animals present on the farm site on around one-quarter to one-third of days. Even when other animals are present, they are often only there for part of the day, rather than the entire day. In October-November 2008, for example, dolphins were present for some period of time on 22 days out of 34 days (2009 Draft EA Appendix 2: Marine Mammal Report from Kona Blue to NOAA, dated 11/26/08). There were dolphins present at the farm site for some or all of the day on 65 percent of the days. On 35 percent of days there were no dolphins reported as observed on the site. On only one day were six dolphins present. Most other days there were one or two animals present for some portion of the day.

Other dolphin species may be found in and around the proposed farm lease area, but are usually most commonly seen on the "grounds" to the south of the site. Spotted dolphins (*Stenella attenuata*), rough-toothed dolphins (*Steno bredanensis*), and false killer whales (*Pseudorca crassidens*) have all been observed on the "grounds" or in other offshore waters of the Kona Coast, but have not been reported from the farm site.

In summation, although there has been behaviour modification in one compromised individual, the presence of the farm operation has not had a significant negative impact on dolphin behaviour.

The overall long-term impact on dolphins from the farm operation is difficult to discern at this stage, but will probably be further reduced. Modifications to net pens currently under way should help to alleviate the attractive nature of the farm to the dolphins, by reducing the potential for escapes through mesh breaches, and for leakage escapes, and by reducing the amount of time that divers need to operate outside of the net pens. Kona Blue will continue with the ongoing monitoring and reporting of marine mammal activity around the farm site, and continues to collaborate in this with HIHWNMS and PIRO PRD staff.

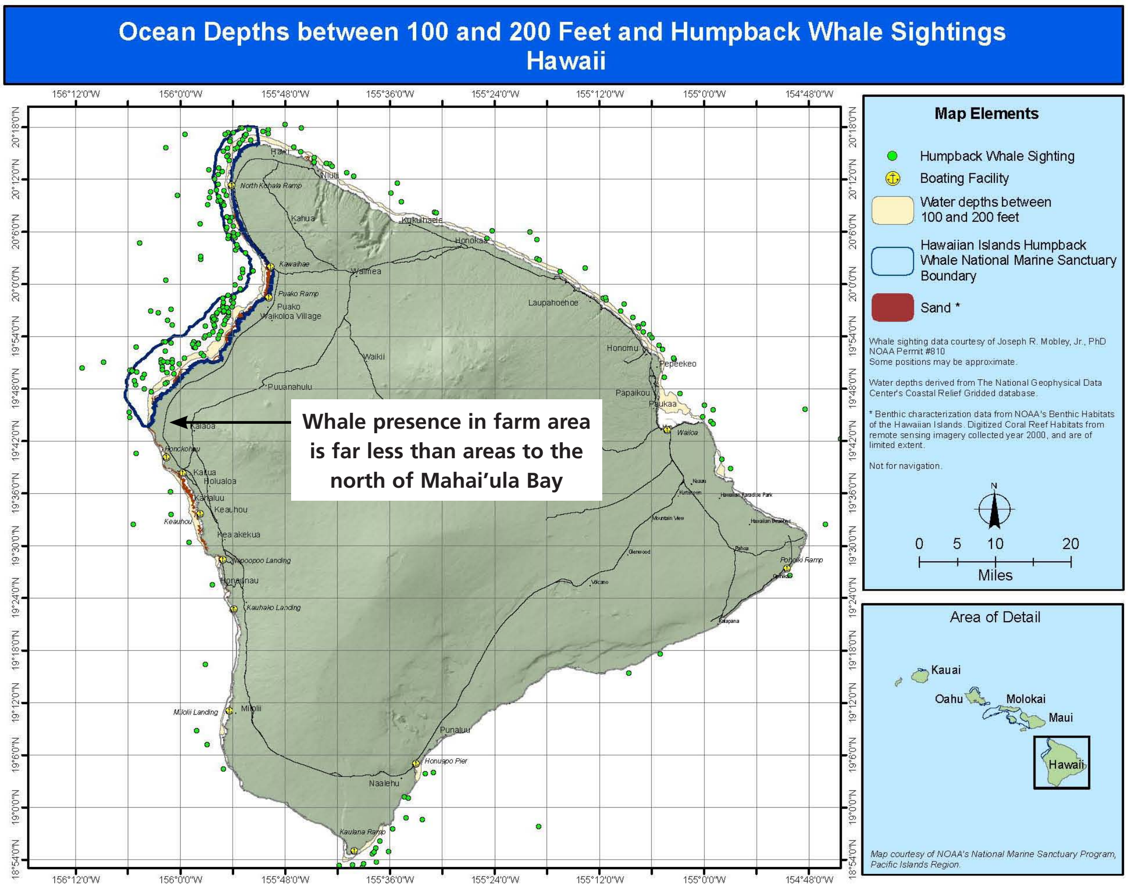
Humpback whales

Populations of the endangered humpback whale (*Megaptera novaeangliae*) winter in the Hawaiian Islands, and the project site lies around one mile (approx. 0.8 km) inside the southernmost boundary of the Hawaiian Islands Humpback Whale National Marine Sanctuary (HIHWNMS). Humpbacks are known to frequent the entire Kona coast area in winter. The whales move throughout the general area, usually following a longshore track (north to south, or vice-versa).

Concerns about the reduction in whale habitat by the existing project were previously expressed by HIHWNMS and DLNR/DAR officials. Some concerns were also earlier expressed with the potential for entanglement of whales in the mooring lines of the net pens. A comprehensive analysis of available records on entanglement by whales (NMFS Stock Assessments), a review of interactions between marine mammals and Hawaii's fisheries (Nitta and Henderson, 1993), and details of marine mammal strandings compiled by NMFS Pacific Area Office (NMFS-PAO) shows that most whale entanglement events occur in slack net mesh (such as drift nets or fish weirs), slack vertical lines (such as crab pot or lobster pot floats), or surface lines (such as long-lining gear). Amongst all these observations, there is no record from any U.S. aquaculture operation of entanglement of humpback whales, or other marine mammals, in the taut moorings or net panels of fish net pens. With heavy mooring gear, and taut lines and mesh, the potential for entanglement is considered negligible (Celikkol, 1999; Wursig and Gailey, 2002).

It further appears that the waters in the vicinity of Keahole Point are not as heavily frequented by the whales as other waters of the sanctuary, further to the north (Figure 9). Observations from workers at the farm site suggest that the farm does not interfere with the movement of the humpback whales, beyond the immediate and obvious exclusion from the waters inside the net pens. The distance of around half-mile (approx. 0.8 km) from the inshore side of the net pens to the shoreline offers ample room for the whales to move around the eastern end of the farm structures, without any chance for any funneling or bottleneck effects.

FIGURE 9
Typical humpback whale sighting patterns around the Big Island of Hawaii



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There is no definitive pattern of whales avoiding, or being attracted to the cages. Whales are occasionally seen within the lease area. On one instance, the farm workers witnessed a humpback on the surface inside the mooring grid array; the animal appeared to negotiate its path between the net pens and mooring lines with ease.

As part of the company's Marine Mammal Monitoring Plan (MMMP), farm workers provide data for assessing whale abundance and patterns of movement around the farm site. The MMMP describes Federal recommendations or instructions in the unlikely event of any entanglement, and also details ongoing reporting requirements for any close interaction with humpback whales, or any physical interaction between the farm array and other marine mammals.

Recreational use impacts

The farm site lies offshore from the Natural Energy Laboratory of Hawaii Authority, and the Kona International Airport, and as such, has little effect on shore-based recreation. The heavily used public recreation area of Kekaha Kai State Park (Mahai'ula) lies more than three miles (approx. 4.8 km) further to the north.

A survey of recreational activity in the general area, north of Keahole Point was conducted prior to the farm installation, from August to September 2001, in conjunction with the original farm site environmental assessment. The survey covered two months of summer conditions, which was considered the best means of ensuring that the data represented the heaviest use of the area. The overarching finding of the survey was that the area is only used for transit: of the 150 observations made over the 61 consecutive days of the survey, only one boat was seen within the farm site – a boat transiting through the area. Most activity in the general Keahole-to-Unualoha area was recreational dive boats and commercial dive tour operations along the reef and shoreline south of Unualoha Point (directly inshore from the farm site), and in Makako Bay itself.

Observations by the Kona Blue staff on the farm site suggest that this trend continues – the only use of the farm lease area is merely transit. Fishing boats now occasionally troll lines close to the central area, to try to take advantage of the aggregative effects of the net pens. There are no records of catch rates around the farm, but anecdotal evidence indicates that catches are primarily "ono" (wahoo, *Acanthocybium solandri*), with infrequent catches of "ahi" (yellowfin tuna, *Thunnus alalunga*).

Kona Blue's permit allows restricted public activities in the lease area, precluding anchoring, SCUBA diving, spear-fishing or swimming within the 90 acres (approx. 36 hectares). These limits are considered the minimum needed to protect the company's investment, to limit their liability (and retain insurance coverage), and to assure public safety. Fishing by the public from unanchored boats (trolling, or line-fishing from drifting boats) is still permitted, but with the caveat that any fishing lines that become entangled in the net pen mooring lines must be left in place, and cannot be retrieved by divers. The company also requests that fishers not troll through the centre of the farm site, because of the potential for fishing lines to entangle divers, or for lures to hook into mooring lines or nets. Boats transiting the net pen area are also requested to observe a slow "no-wake" boat-speed, to maximize safety for divers. Unguided recreational SCUBA diving or unauthorized commercial SCUBA dive tours are not permitted within the lease area, because of liability, safety and security concerns.

The loss of access to recreational activities within this relatively small area of ocean space is not considered significant. Kona Blue's ongoing observations affirm that there is virtually no fishing or other recreational use of the lease area, or the areas adjacent to the lease area, beyond trolling, which is probably enhanced by the farm's presence.

Viewplane aesthetics

Community value judgments and perceptions of how the oceans should be used largely govern the impact of the project on the community's aesthetic enjoyment of the area.

In community meetings, Kona Blue generally enjoys strong support for the broad goals of the company. There is wide recognition of the severely depleted status of bottomfish species in Hawaii. The awareness of the global fisheries crisis has recently been amplified by several scientific studies, such as that of Worm *et al.* (2006), which projected a collapse of world fish stocks by 2048, unless significant remedial changes are made to fisheries and marine ecosystem management.

The visual impact of the project is minor, compared with the adjoining properties of Kona International Airport and the aquaculture operations at NELHA. The major visual impact from the farm operation is from the experimental surface pens and the feed barge. There is also the additional presence of work and dive boats, and harvest boats, on some days. However, the impacts of these structures and activities are not significant, given the distance from the nearest residences, more than 3 miles (approx. 4.8 km) away.

There is general community acceptance that the project fits in well with the overall ambience of innovative aquaculture at NELHA, and the need for Kona to develop alternative industries beyond tourism. Fisherfolk and other mariners recognize the validity of the criteria that Kona Blue has used to select this site (c.f. deeper or shallower sites), and have not expressed a strong preference for the project to be located elsewhere. Applicants for farm permits in other areas of the Kona Coast (around Kawaihae) have, on occasion, been told that their project would more appropriately be located "down near NELHA and Kona Blue".

Cultural resources, practices, and mechanisms for impact

The farm lease area is too deep for free-diving or SCUBA diving activity, except for "blue-water" spear fishing. Usually, however, blue-water spear fishing is practiced close to a point or drop-off, rather than over bare sand substrate around 200 ft. (approx. 61 m) deep. There are no significant benthic plants or animal populations in the farm lease area, and there are virtually no benthic or pelagic fishing activities in this depth range. Kona crabs and "nabeta" (*Xyrichtys pavo*) are the only benthic resources that occur on sand bottom at this depth, but informants suggest that the currents are too strong for any significant fishing effort this close to Keahole Point (R. Punihaole, personal communication, 2003).

The only potentially-impacted cultural resource that was cited during extensive discussions with community and kupuna (elder) groups for the original farm site was the several 'opelu ko'a ("holes" or schooling places for mackerel scad – *Decapterus macarellus*) that occur in the general region. The locations of these ko'a are considered to be part of traditional marine lore, and are considered inappropriate for publication, or for sharing outside of the families or community groups who have traditionally fished these ko'a. However, in private meetings with the most knowledgeable kupuna, the locations of the traditional 'opelu ko'a were determined to be outside of the proposed project location. 'Opelu aggregations usually occur in water around 120 ft. (36.5 m) deep, close to reef drop-offs, and well shoreward of the farm area.

Prior to the 1801 lava flow that inundated the area, Keahole was the site of the largest fish pond in the Hawaiian islands. The Pai'ea pond (reputedly King Kamehameha's favorite pond) was approximately three miles long and one-half mile wide; canoes were used to traverse from one side to the other. The farm site is directly offshore from where Pai'ea once stood. Fish farming could therefore be considered historically and traditionally appropriate to the area.

The farm site constitutes part of the Hawaiian ceded lands trust, since all submerged lands are ceded lands. The 1999 amendments to the Ocean and Submerged Lands Leasing law (Chapter 190D HRS) directly addressed the issue of Office of Hawaiian Affairs' share of the lease revenues, by stipulating that the designated 20 percent of lease payments should be due to OHA.

The public perceptions of ocean access and ownership in Hawaii are an amalgam of two conflicting cultural traditions. The legal regime has, up to now, been largely based on the ancient western concept of *Mares Librum* – Freedom of the Seas, or the ocean as a common property resource. The traditional Hawaiian concepts of land-use and ocean-ownership practices were related to the principles of the ahu-pua'a, fish ponds and the konohiki fisheries. This provided for ownership of ocean resources and was recognized as a sustainable, efficient means of managing the ocean and reducing conflicts.

The 1999 amendments to the Ocean and Submerged Lands Leasing law (Chapter 190D HRS) were the first major step to view the oceans as a resource that could be occupied and sustainably utilized, rather than simply exploited. This represents a change in the legislative and community thinking. It could be interpreted to represent a shift in current policies away from the Western *Mares Librum* ideas towards the more traditional Hawaiian concept. It might also reflect increasing recognition – evident in increased regulation and licensing of fishing activities in the state – that open-access fisheries and unrestricted access to the ocean does not appear to provide sufficiently for effective management of ocean resources.

Access to or practice of any other customary activities has not been significantly constrained by the farm array or operations. The exclusive control over the waters (and the fish) inside the net pens is consistent with traditional and cultural practices that identified fish traps or lobster traps – and the animals therein – as the private property of the trap owner. The same principles apply here.

The actual observed impacts: globally

Fishmeal and fish oil usage

Fish such as *Seriola rivoliana* usually feed towards the top of the trophic chain in the wild. They therefore possess digestive systems and nutritional requirements that are adapted for feeds with high protein and lipid levels, and low levels of carbohydrates.

Fishmeal and fish oil usage in fish feeds is considered a valid use of a natural, sustainable, renewable resource, so long as the fishery from where the fishmeal and fish is sourced is responsibly managed. Although stocks such as the Peruvian anchoveta fishery are sustainable in the sense that they are very well managed, they are not scalable. If mariculture is going to fulfil its potential for increasing seafood consumption to meet growing demands, then some alternative sources of proteins and oils will be required.

Kona Blue has therefore, been focused on reducing the inclusion rate of fishmeal and fish oil from targeted reduction fisheries, such as Peruvian anchovies, and increasing the use of agricultural oils and proteins, such as soy, canola, wheat, corn and poultry meal and oil.

Improving feed conversion efficiencies: an evolutionary approach

Though efficient use of fishmeal and fish oil from targeted reduction fisheries is both rational and justifiable, this by no means suggests that these resources are unlimited, or we should not search for alternatives. If open ocean mariculture is to develop into a food production system that can provide a significant proportion of the nutritional needs for a growing planet, then we must find additional sources of sustainable proteins and oils for feedstuffs for this industry. The arc of Kona Blue's feed development strategies is perhaps instructive of directions that open ocean mariculture, as a global industry, might follow to achieve such scalable sustainability.

Initially, Kona Blue Water Farms fed the Kona Kampachi® with a diet that was considered "organic" by European standards. At the time, USDA did not have (and still does not have) organic standards for aquaculture feeds. In the EU, however, organic fish food was considered to be that which is most similar to the animal's diet in the wild. This feed, therefore, was comprised largely of fishmeal and fish oil derived from Peruvian anchovies.

With recognition of the need for more scalable feedstuff alternatives, however, Kona Blue worked with the feed vendor to develop a new diet that lowered the inclusion rate of fishmeal and fish oil from Peruvian anchovies to 50 percent. This diet included soybean meal, wheat gluten, canola, and other grain proteins and oils. The biological efficiency for this diet, however, was still suboptimal, with a Fish-In:Fish-Out ratio (FIFO) of around 3:1. (i.e. an input of 3 lbs [approx. 1.35 kg] of anchovies for each pound of Kona Kampachi® produced).

The inclusion rate of agricultural proteins in diets for marine piscivorous fishes is limited by the presence of a range of "anti-nutritional factors" in the grains and less-purified meals. (Note: although often described as carnivorous, most marine fish such as groupers, snappers, jacks, and bream, are perhaps more accurately described as "carbohydrate intolerant". They require diets that are high in protein and lipid, and low in carbohydrate. There is no specific nutritional requirement that these fish eat meat). For this reason, soybean meal is restricted to about 20 percent of the diet for most marine fishes. To reduce the fishmeal and fish oil inclusion rate further, and to further lower the FIFO, would therefore require proteins and oils from other sources. By-products from both edible fishery processing and poultry processing were therefore included in the revised Kona Blue diet, allowing the Peruvian anchovy inclusion rate to be further reduced to 30 percent of the ration, or 20 percent fishmeal and 10 percent fish oil.

Inclusion of poultry processing by-products, however, meant that some customers, such as Whole Foods Markets (WFM), a high-end organic and natural foods retailer, would no longer carry Kona Kampachi®, even if the poultry used for the by-products was of organic origin. This position by WFM was out of consideration for those of their customers that were vegetarians, but still wanted to eat fish. WFM asserted that these customers would not want to eat fish if that fish had eaten a pellet that contained proteins or oils that were derived from mammals or birds. Kona Blue appealed to WFM to review their position, given the importance of reducing our global footprint on the oceans – i.e. our reliance on natural marine resources, but as of 2010, there has been no change in this policy.

Kona Blue has recently tested two diets that completely eliminate from the Kona Kampachi® diet any fishmeal and fish oil sourced from targeted reduction fisheries, and any land animal processing by-products. These innovative diets use processing by-products from sustainably-managed fisheries intended for human consumption. As the trimmings from these sources would otherwise have been discarded, used as fertilizer, or burnt as fuel, the use of these fishmeal and fish oil products in the Kona Kampachi® diet represents an ideal re-use of natural resources. These diets therefore would result in a zero FIFO ratio – i.e. no targeted reduction fishery by-products included in the diet of the end product.

Alternative feedstuffs for open ocean mariculture

Kona Blue is involved in testing a range of alternative feedstuffs for Kona Kampachi® diets, which also offer potential for other species of marine fish. Alternative soy products, other agricultural grain concentrates, yeast and other single cell proteins, edible fishery by-products and – more recently, with the boom in microalgae culture for biodiesel production – defatted microalgae by-products have all either been tested, or are under development for Kona Kampachi® feed trials.

Kona Blue has tested a range of soy-based diets, with soy protein concentrates and omega-3 oil rich strains of soybeans. These trials suggest that the inclusion rate of soy protein concentrates cannot, by itself, exceed the same 20 percent threshold that limits soybean meal. Above this level, growth rates and feed conversion ratios are depressed. With the inclusion of taurine in the formula, however, soy protein concentrates could replace fishmeal as the source of protein up to 40 percent of the diet with no detriment to fish growth rates or feeding efficiencies.

There is a diverse array of edible fishery processing by-products that are available for use in aquaculture diets, and this direction offers tremendous potential for further development. The processing by-products from most wild salmon runs, for example, are woefully underutilized, and are often disposed of directly back into the rivers from which the fish are taken. Logistical and economic constraints limit the use of these trimmings, however, as the processing plants are usually small and isolated, the salmon runs are of only short duration, and storage and transport of fishmeal or fish oil by-products from these villages to fishmeal or fish oil reduction facilities, or feed mills, is challenging. Development of fish silage systems offers one potential, partial solution. However, even the less-seasonal, larger-scale processing of farmed salmon in more centralized plants presents difficulties for utilization of by-products. For bio-security reasons, most fish feed plants will not run salmon-derived feed stuffs through their machinery, because of the potential for contamination of feeds from viruses, bacteria or other pathogenic vectors that may be found in the by-products. Screening for known pathogens is not an adequate solution: even though the chance could be considered very slim that some unknown pathogen may be unwittingly dispersed via extruded feed, the potential catastrophic consequences of such widespread and rapid disease dissemination are sufficient to ensure that no such chance be offered. This therefore excludes almost all large feed mills in salmon-farming regions from using salmon by-products.

Similar inefficiencies are found in re-use of trimmings from the pollock fishery (*Theragra chalcogramma*) in the northern Pacific. This fishery primarily processes most of the catch at sea, into surimi. Trimmings from these fish constitute around 65 percent of the wet weight of the catch. For a fishery that has averaged around 1.3 million tonnes, this then represents around 850 000 tonnes of wet weight by-product annually that could be converted into fishmeal and fish oil. For many years, much of this by-product was discarded back into the ocean, or the rendered fish oil was burnt in the diesel generators of the processing vessels. Some 8 million gallons (approx. 30 million litres) of fish oil in Alaska (United States of America) is largely disposed of as bio-diesel (Alaska Energy Authority, undated). More recently, some proportion of these trimmings have been used to make a high-quality white fish meal that is largely exported to Asia, where it is valued in feeds for farmed eels. However, the proportion of by-product that is re-used or recycled is not reported. Again, economics and logistics conspire against development of a rational supplement to targeted reduction fisheries. With increasing prices for fishmeal and fish oil, however, driven by growing demand for animal feeds from developing economies (notably China and India) there may be greater incentive to resolve these constraints. Edible fishery by-products may yet play a significant role in aquaculture feedstuff sourcing.

There is ample evidence that some or all of these innovative feedstuffs could help to reduce the demand for fishmeal and fish oil from clupeids in the medium- to long-term. Removal of this last constraint to growth should then see a true “blue horizon” of opportunity dawn for open ocean mariculture: a future food production system that can feed the world, without any significant negative impacts on the ocean environment. The Kona Blue example suggests that this is indeed achievable. The challenge, going forward, is for us to grow this industry in a manner that provides the best chance for what is achievable to become a reality.

Aquaculture in the food chain

Much interest has been recently focused on the problem of “fishing down the food chain” (Pauly *et al.*, 1998; Taylor *et al.*, 2000). This is the trend over time for commercial fisheries – driven by serial stock depletion – to shift their target species to those lower on the trophic pyramid. Fishers first start out exploiting the high-value, top-end predators, then move on to mid-level predators, and then on down towards herbivores and detritivores – what was previously considered bycatch. Fisheries generally start out targeting the larger, sweeter-tasting species – tunas, snappers, groupers, and such. As these become increasingly scarce, fishers apply greater fishing power, and fish longer and deeper, retaining or targeting what was previously considered "trash". The argument portends that at some stage, the food web is reduced to an ocean full of jellyfish. "Fishing down the food chain" is a condemnation of the inherent unsustainability of most commercial fisheries management – or rather, mismanagement.

Fish farming has somehow been implicated in this practice, on the basis that farmed fish are fed pellets that are partly comprised of fishmeal and fish oil derived from anchovies, menhaden, sardines or the like. These fish (collectively, the clupeiforms) usually form the first step in the ocean food chain beyond primary production. Some scientists and anti-aquaculture advocates misconstrue or deliberately misinterpret the complexities of ecological and economic cause-and-effect, and represent the use of clupeiforms as feed for farmed fish as wanton. This has been led by respected institutions such as the Monterey Bay Aquarium, but has also spilled into mainstream media, such as the New York Times, Conservation Magazine's article on "10 Solutions to Save the Ocean", The Ecologist and the Economist. The notion that aquaculture is guilty of "fishing down the food chain" is now lodged within the public consciousness.

The bottom of the food chain, however, is where we should preferentially be fishing. It makes far more sense to use herbivores or planktivores from the base of the trophic pyramid as either human food or feed for farmed fish, than to be targeting top-end predators. This makes economic sense, but it also makes sense from other perspectives: it is better for the ocean's ecosystems, it is better from the viewpoint of bioenergetics transfer through the trophic pyramid, it is better for consumer health, and it makes for better fisheries management.

The economics are simple: Peruvian anchovies and menhaden are not highly valued in the market, so they are cheap. Maybe this will change in time, and prices for anchovies and sardines will increase, as more people develop a taste for oily baitfish, but it is more likely that most consumers will still prefer larger piscivorous marine fish as sashimi or fillets.

The ocean's ecosystem offers several reasons why the bottom of the trophic pyramid is a better place for us to extract our nutrition from the sea. It is, most simply, a matter of mass and mathematics. Herbivorous fish are more abundant, with greater biomass. To catch 1 000 tonnes of Peruvian anchovies has little impact on the 6 million ton spawning biomass (around 0.025%). By contrast, 1 000 tonnes of tuna represents around 10 percent of the bluefin tuna spawning stock in the Western Atlantic: the biomass of which is currently estimated at less than 10 000 tonnes.

Moreover, Clupeiforms are classic "R-selected" species: smaller body-size, faster maturing, with shorter life spans. They are highly opportunistic: a decrease in population size in Peruvian anchovies often results in increased recruitment from the next spawning. From an ecological perspective, these species are precisely where fishing effort should be targeted; not on the larger, more vulnerable, slower-growing "K-selected" species at the top of the food chain. In agricultural terms, most of the crops that humans raise are strongly "R-selected" – wheat, corn, barley, rice, while targeting a "K-selected" species in agriculture might be the equivalent of chopping down oak trees to eat the acorns.

Herbivorous clupeiforms also grow and reproduce faster. Menhaden stock resilience to fishing pressure is "high", with a population doubling time of only 15 months. Northern bluefin tuna, by contrast, have "low" stock resilience, and a minimum population doubling time of 4.5–14 years. If half the menhaden were harvested, it would therefore take 15 months for the stock to recover. However, if half the tuna population was taken, it would take – at a minimum – between 4.5 and 14 years to recover. Southern bluefin tuna also do not begin to spawn until they are perhaps

11 years old, and may live to "at least 40 years of age". However, Peruvian anchovies are sexually mature within one year, and only live for around three years. The 3-year old anchovies then die and fall to the ocean floor.

The public health imperative should also provide impetus to source fishmeal and fish oil from lower down the food chain. Menhaden and anchovies filter algae and zooplankton directly from the water. They are therefore, high in heart-healthy omega-3 oils, yet low in the persistent organic pollutants, such as mercury and polychlorinated biphenyls (PCBs). These pollutants, however, are concentrated as they move further up the food chain. It is primarily top-level predators – sharks and tuna – that are on FDA advisories for pregnant and nursing mothers and children. By contrast, an aquaculture species that can achieve a feed conversion efficiency of close to 1:1 (FIFO or Fish-In:Fish-Out) contain essentially the same contaminant loading as the clupeiforms at the base of the food chain.

Clupeiform fisheries are also more readily managed, with relatively simple stock dynamics and ecosystem interactions. The major inputs to clupeiform stocks are the spawning biomass and primary productivity, which is usually driven by the strength of the nutrient-rich upwelling. Most of the fisheries occur within the EEZ of a single nation, where there are direct incentives for sound management and enforcement, and where access can be regulated. Tuna and swordfish, by contrast, are highly migratory species. Donut-holes of high-seas waters, beyond any country's 200-mile zone (approx. 322 km), provide opportunities for distant-water fishing nations to concentrate their boats and effort. Attempts at managing tuna stocks are typified by the International Commission for the Conservation of Atlantic Tunas (ICCAT), which has 46 Members and almost no enforcement capabilities. And while Hawaii's longline fishery targeting big-eye tuna may be very well managed, for example, heavily-subsidized European or Asian purse-seiner fleets target the juveniles of the same stock in the South-Western Pacific.

Moreover, the carbon footprint of clupeiform fisheries is minimal. These fish are usually taken by purse-seiners, working close to the coast, encircling schools containing hundreds of tonnes at a time. The carbon footprint for species higher on the food chain is much higher, with fish caught by diesel-powered trawlers or trollers, or – for blue-fin tuna and swordfish – harpooning the fish, one at a time.

Most importantly, however, it is far better from a bioenergetic perspective to target fish closer to the bottom of the food chain. Applying the 10 percent trophic transfer rule means that the one pound (approx. 0.45 kg) of wild tuna sashimi on a consumer's plate needed to eat ten pounds (approx. 4.5 kg) of anchovies – or the equivalent in fishmeal and fish oil. Or maybe, if there were two steps in the trophic pyramid, each pound of wild tuna required 100 pounds (approx. 45 kg) of anchovies to first be converted into ten pounds (approx. 4.5 kg) of mackerel.

Aquaculture, by contrast, is always a single step – clupeiforms-to-crop. But aquaculture can also use alternative agricultural proteins and oils, such as corn and wheat gluten, soy proteins and oils, canola and other animal processing by-products. These other proteins and oils reduce the fishmeal and fish oil inputs, to where some of the purported "carnivores" can thrive on a diet that is around 20 percent fishmeal and fish oil. On the "sustainability quotient" – the number of pounds of fish-in to produce one pound of fish-out (the FIFO) can then attain the perfectly efficient goal of parity or 1:1 (i.e. every pound of Peruvian anchovies in the farmed fish diet produces one pound of product). The result is efficient conversion of a low-value anchovy into a high value marine fish, without disrupting the fragile top of the trophic pyramid.

Larger, wild fish are more bio-energetically wanton. Wild fish lose energy through inefficient digestion, in hunting prey, trying to avoid predation, spawning, and succumbing to natural mortality. As wild fish grow larger, so too do they become increasingly inefficient – a greater proportion of energy is needed to maintain the animal's metabolism. Any by-catch will compound these inefficiencies further. The global by-catch ratio is around 0.28 lbs of discard for every pound of target species.

Earlier estimates suggested that farmed fish might be more efficient than wild fish, based on a single trophic step, by a factor ranging from two to five. Combining the life-cycle inefficiencies, trophic inefficiencies and by-catch inefficiencies of wild fish, however, means that farmed fish may be more efficient than wild fish by a factor of around 60 (Table 1).

This reasoning does not advocate for greater fishing effort on anchovies. To the contrary – caution is called for. While most of these stocks are sustainably managed at current levels, they could not withstand any greater pressure. These clupeiform stocks should continue to be very closely monitored, and highly regulated. Large marine protected areas should also be established to allow some clupeiform-based ecosystems to flourish in their natural state (rather than attempting ecosystem-based management). But it is imperative that we should better manage the fisheries at the base of the food chain, and endorse environmentally sound aquaculture, so that we can safely take pressure off the top of the food chain.

Fishing at the bottom of the food chain should therefore be encouraged preferentially over any other kind of fishing. This is not a function of recent overfishing: even 100 years ago, this principle would have still held true. We always should have been fishing at the bottom of the food chain. To continue to accuse aquaculture as being part of the

TABLE 1

Relative ecological efficiencies of farmed and wild-caught fish. The table shows the compounded cost in terms of anchovy-equivalents for farmed and wild-caught fish. Low-end estimates and high-end estimates are provided for each type of fish, and compared cross-ways to obtain a lowest-relative rate and highest-relative rate

	Farmed fish		Wild-caught fish		Global mean
	Low-end estimate	High-end estimate	Low-end estimate	High-end estimate	Ratio of wild to farmed
Life-cycle efficiency[1]	1	1	3	10	6
Trophic transfer efficiency[2]	1	8	10	100	7.3[3]
"Bycatch" efficiency	1	1	1[4]	11[5]	1.3[4]
Compounded "cost"	1	8	30	11 000	57

Note: The lowest relative rate extrapolated from this table is that the least-sustainably-farmed fish are around 4× more ecologically efficient than the most sustainably-harvested wild fish (i.e. 30:8). The highest relative rate is that the most sustainably-farmed fish could be 11 000× more ecologically efficient than the least-sustainably-harvested wild fish (i.e. 11 000:1). The Global Mean of wild fish efficiency to farmed fish efficiency is around 57×.

1 There are no published estimates of the relative life-cycle efficiencies of farmed vs. wild fish. However, fish that reach reproductive age in captivity can see feed conversion ratios increase by factors of 5 or 10 over juvenile and subadult fish. Natural mortality and the nutritional cost of maintenance of basal metabolic processes during periods of food depravation also increase the "economic" feed conversion ratio for wild fish populations.

2 In 1997, food conversion efficiencies (FCE) for farmed marine fish and farmed salmon were around 5:1 and 3:1, respectively (Naylor *et al*., 2000). By 2010, however, FCEs are projected to reach 1.5:1 for farmed marine fish, and as low as 1.2:1 for farmed salmon (Tacon, 2005). Kona Blue has been able to culture Kona Kampachi® on a diet that equates to a 1:1 ratio of wet-fish-in to wet-fish-out. However, if a less-sustainably-farmed fish is fed a pellet high in fishmeal and fish oil (say, to meet the Scottish Soils Association's Organic standards, with around 80 percent fishmeal and fish oil), this diet could equate to around 4 lbs (approx. 1.8 kg) of wet anchovy-equivalents for every 1 lb (approx. 0.45 kg) of dry pellet (a wet-fish to fish-meal ratio of 5:1 is considered standard). On this diet, most commercially-farmed species might have food conversion ratios of around 2:1 (dry-pellet to wet fish), implying an FCE of 8 lbs (approx. 3.6 kg) of wet-fish-in for every one pound (approx. 0.45 kg) of wet-fish-out.

3 Tacon's (ibid) estimate of FCEs for farmed salmon and farmed marine fish might be conservatively pooled at, say, 1.5:1 – i.e. 1.5 pounds of anchovy-equivalents for every pound of farmed fish produced worldwide. There is a differential of around 1.1 trophic levels between global fishery landings (with a mean trophic level of around 3.3), and the Peruvian anchovetta fishery (with a trophic level of around 2.2; Pauly *et al*., 1998). At a presumed 10 percent biomass transfer efficiency up each trophic level, implies 11 pounds (approx. 5 kg) of anchovy-equivalents to produce a pound of harvested wild fish. The median ratio of wild to farmed trophic transfer efficiencies can therefore be estimated at 11:1.5 or 7.3:1 overall.

4 Harrington, Myers and Rosenberg (2005) report a "nationwide discard to landings ratio of 0.28" (i.e. for 3.7 million tons landed, some 1.06 million tonnes were discarded). However, for highly-selective fishing methods, such as harpooning, by-catch is effectively zero as for farmed fish.

5 "For finfish, the ratio of bycatch to target fish (in the Northern Pacific) can be as high as 11:1 because the bycatch is either too young, out of season, or the vessel has no permit to keep it." (Alverson, 1998).

problem of "fishing down the food chain" is therefore, disingenuous. Aquaculture is an important part of the solution for how we should feed our growing humanity. To assert otherwise is confusing to the consumer, and is discouraging the policy shifts that we need to make towards more sustainable aquaculture and healthier oceans.

THE IMPEDIMENTS

Overcoming the antagonism to aquaculture in major markets

In many parts of the Western world, the major impediment to expansion of open ocean mariculture is a generalized negative association with fish farming, or concerns with privatization of the oceans. This is most robustly manifested in the anti-salmon farming lobby: an extensive group of NGOs throughout the US Pacific Northwest and Canada, and parts of Scotland, Ireland and Norway. This lobbying is supported by private foundations, such as the Pew Environmental Trust, the Moore Foundation and the Packard Foundation.

Although much of the opposition to mariculture stems from salmon, the lobbying is becoming more widely opposed to the farming of other marine fish. The litany of objections listed by these groups includes all of those discussed above, but is perhaps more honestly portrayed as a philosophical opposition to the involvement of multinationals in the aquaculture industry (Pauly, 2009). Even though environmental standards and farm practices were previously far more rustic in the 1980s and 1990s, it was only with growth and consolidation of the industry since around the new millennium that the opposition has reached this new level of intensity.

With growth of a new industry of the scale and rapidity that salmon farming has seen, there are indeed very real risks that subsistence or artisanal fishers will suffer disenfranchisement or face commercial competition for limited resources. However, rather than creating economic inefficiencies by opposing the growth of the new industry, such concerns may perhaps be more effectively met with other initiatives or management measures. For example, if the concern is the consolidation of the industry, then it may be more appropriate for legislation to limit the extent of stakeholder dominance through anti-trust laws, or a "quota" over farm areas. If the concern is the targeting of small pelagic fish stocks for reduction into fishmeal and fish oil, then – instead of actively discriminating against the farming of higher trophic level fish – governments with jurisdiction over these stocks might rather limit access by foreign fleets, or establish catch quotas or preferential area access to artisanal fishers who are selling into local markets for human consumption. Governments might also provide loan or tax incentives for construction of canneries for anchovies or sardines. Governments in countries where marine fish farming shows most growth potential may – instead of restricting such growth and placing their entrepreneurial and investment resources at a disadvantage with other countries – instead choose to support fish nutritional research, or development of alternative protein and oil resources.

On a global level, there should be far more focus on optimum use of fishmeal and fish oil resources. At-sea processing vessels often dump fish trimmings overboard, when these resources might find better use in marine fish diets. In the United States of America, tax incentives are available for pollock processing vessels to burn the fish oil residues in their diesel generators, and thus defray their reliance on imported fossil fuels. Given the human-health value of fish oils, this practice seems to be even more egregious than the more generally recognized competition between energy and nutrition: the much-derided use of corn and other grain crops for ethanol production. There is also a need for development of efficient means of processing and transport of edible fishery by-products from geographically dispersed or seasonal fisheries, such as Alaskan salmon fisheries. Processing plants for salmon runs in remote areas often dispose of trimmings and carcasses directly into rivers, rather than undergo the technological and logistical challenges of stabilization and transport of the by-products, or silage or meal and oil (fish processing vessels in Alaska, United States of America, are permitted under their NPDES permits to dump up to 3 million pounds [approx. 1.36 million kg] of wet fish offal per year into any one square nautical mile area).

It is both undesirable and inefficient to encourage use of by-catch for reduction purposes. Management and development agencies should not be providing any incentives for alternative use of fish that are undersize, over quota or otherwise unsaleable. In addition, the taxonomic diversity of by-catch means that there is little consistency in the make-up of the catch, which would result in fishmeal and fish oil of varying qualities. This significantly diminishes the commercial value of these products for use in compound feeds for mariculture.

But the activist-driven negativity towards aquaculture already influences national policies, and may further hinder the rational and responsible development of open ocean mariculture, with consequent detriments for the ocean environment, for human health and for economic activity. Repression of open ocean innovation or entrepreneurial activity in one country or region will simply drive it elsewhere – either into international waters or into countries where monitoring and regulation are inadequate and rents are lowest. This forcing of offshore mariculture would appear to be counter to the best interests of governments, peoples and the environment.

There would therefore appear to be justification for the Food and Agriculture Organization of the United Nations (FAO) to play a leadership role in co-ordinating the accumulation and dissemination of objective, factual information on the impacts of open ocean mariculture, the most appropriate means of monitoring operations, and the best way of regulating the industry's growth.

There may also be some call for cautious optimism: in the face of the continuing commercial pressure on wild fish stocks, the overwhelming evidence in favour of increasing seafood consumption, and the gradual accumulation of evidence that open ocean mariculture – if conducted responsibly – can avoid most of the negative impacts normally associated with nearshore systems, there is some gradual – if begrudging – acknowledgement from some leading academics and NGOs that aquaculture may be an essential and desirable part of seafood and oceans policies. A 2009 life cycle analysis (LCA) of all seafood production and distribution systems concluded that the differences in carbon footprint between farmed and wild-caught seafood was inconsequential, compared with the stark differences between seafood that is delivered to market fresh by airfreight, and that which is delivered through the frozen supply chain, by seafreight or trucking (Pelletier *et al.*, 2009). Naylor *et al.* (2009) recently touted the "impressive gains" in FIFO ratios for aquaculture, and highlighted the mean global FIFO of 0.63:1 for all aquaculture (i.e. net protein production). Ocean Conservancy Magazine (Fox, 2009) carried a cover story about the opportunity for environmentally-responsible open ocean mariculture entitled "Farmed fish: Getting it right from the start".

But many of the anti-aquaculture activists have direct interests to continue perpetuating the myths and misinformation in the media and the public's minds. Without an aquaculture crisis to stimulate public donations or drive foundation-funded research, the support for many activist groups is severely curtailed. There is therefore still a long way to go before these entrenched interests are overcome, or they are reconciled with the reality of what needs to happen in our seas, and where and how this must happen.

Lack of legislation

Legislation in national waters

Many countries do not presently have legislation for open ocean mariculture beyond their coastal waters. These regulatory vacuums both discourage investment and innovation, and also run the risk that commercial projects will become established and grow in an unplanned manner. Many countries are recognizing the need for broadly-based marine spatial planning, and offshore mariculture should be an essential component of such initiatives.

Most activities in nearshore waters are administered by state or local agencies, where the interests of competing user-groups can perhaps be better voiced and adjudicated. The regulation of activities in deeper waters, further offshore, however, more naturally falls under the jurisdiction of national governments. State and local governments have historically extended their rights only into territorial waters, and the expanded EEZs are administered on a national level. However, few national governments possess the legislative or regulatory frameworks for supporting applications for mariculture leases or permits within their EEZs, or for monitoring and regulating the activities.

There would appear to be a role for FAO in supporting regional fisheries management agencies and national governments in developing such policies and frameworks.

Regulation of activities on the high sea

There would also appear to be a need for leadership from FAO in co-ordinating the regulation of open ocean mariculture on the high seas, beyond 200 mile (approx. 322 km) boundaries. Although often dismissed as science fiction, the powerful economic incentives of the tightening seafood supply chain and restricted access to more nearshore waters are combining to drive innovation in this direction. The attraction to international waters is also driven somewhat by biology: in deeper waters, fish health concerns and environmental impacts are reduced to *de minimums*, becoming essentially perpetual fallowing sites, and mobile fish farm platforms may find advantage in positioning in water masses with optimum temperatures for fish growth.

The "trans-ocean drifter cages" that have been depicted in popular media (e.g. Wired Magazine) have caught much public fascination, but are not practical with today's technology. There are also logistical challenges of sustaining operations in mid-ocean by providing feed and staffing for long periods. However, the initiation of discussions on high seas regulatory framework for mariculture by FAO would not be inappropriate, and may abet and hasten the development of these technologies.

Technological and capital requirements

There still remain some significant technological, economic and operational challenges before open ocean mariculture can truly fulfil its potential. Primary amongst these is validation of the commercial viability of submersible net pen technology in exposed ocean locations, where currents are unpredictable and strong, and where sea states may regularly exceed the relatively calm seas of Kona.

There are pressing needs for larger net pens to allow greater operational efficiencies, and increased automation to remove or reduce the reliance on SCUBA diving for servicing the net pens. Routine tasks such as remote feeding, automatic retrieval of mortalities and net cleaning must be able to be accomplished in submerged net pens without divers. The underlying technologies for these tasks appear to be available off the shelf (such as ROVs, and remote video links), but the components have yet to be integrated and tested on working farm sites. Kona Blue is pursuing some of this work in conjunction with Lockheed Martin, as part of a National Science Foundation research project, and other companies and research institutes, such as University of New Hampshire, are also directing increasing attention to these fields.

Submerged cages can be difficult to manage in terms of handling of the cages, cleaning of the net mesh, and management of the fish stock, given the inability to fully apply mechanical advantage (it is difficult to bring boats alongside submersible net pens, and the barrier nets do not readily allow functions such as seining), and the diving requirements. Almost all work around submerged cages requires SCUBA diving. This is both a heavy burden on the practicality of operations, as well as an onerous economic burden on a company's bottom line. In the United States of America commercial diving regulations require four workers to undertake any SCUBA-diving task (two divers, one dive supervisor, and a back-up diver), essentially quadrupling the payroll burden. SCUBA diving insurance rates are also very costly. Additionally, the heavy reliance on SCUBA-diving limits participation by commercial fishers in the offshore fish farming industry.

Ocean currents over one knot (50 cm/sec) occur frequently at the Kona Blue farm site, and other potential offshore aquaculture sites. As these currents are driven by ocean gyres, they do not follow predictable tidal/lunar cycles, and therefore are not predictable in strength or periodicity. This can significantly impact work with the submersible cages and with other tasks such as transferring fish or seining. The Sea Station cages can be sometimes held underwater by strong currents, preventing harvest, collection of mortalities, cleaning or other diver work. US Federal Occupational Safety and Health Administration (OSHA) dive regulations preclude any diving in currents over one knot. OSHA dive rules also require that there be an air-gap at the top of any enclosed space before SCUBA divers may enter; this effectively eliminates any work inside a submerged cage, and dictates that cages must be raised to the surface for even the most routine of tasks, such as removing mortalities.

The nylon netting on submersible cages has also proven difficult to keep clean, requiring diver-operated high-pressure net washing machines to remove biofouling. It takes between 2–4 days for divers to clean a single cage (i.e. 6–12 man-days, with a crew of three). Excessive fouling on the net material, resulting from infrequent pressure-washing, can exacerbate fish health in *Seriola* culture. The biofouling acts as a reservoir for eggs of the highly pernicious skin fluke, *Neobenedenia* spp. This ectoparasite is the major challenge for most yellowtail farming operations around the world. Losses due to skin fluke infestations and related infections – particularly for the more vulnerable juvenile fish – have resulted in significant lost revenues for Kona Blue. The inability to corral the fish in a fixed volume cage also makes it difficult to efficiently seine the fish, which can prevent effective treatment with therapeutants or vaccines.

In addition, the Dyneema netting on the Sea Stations in Kona has proven vulnerable to predators (*Seriola rivoliana* is native to the area and Kona Blue undertakes no selective breeding in the hatchery, so the ecological impacts from such escapes are not significant). Kona Blue has conducted tests with the recently-available Japanese rigid plastic netting material: Kikkonet®. This material offers significantly greater protection from predators, with no risk of entanglement, and – because of the monofilament nature of the material – easier cleaning. The life-span for Kikkonet is also reputed to be far longer than nylon nets: 20–30 years.

Submersible cages may also not be the most efficient cages for feeding the fish stock. The bi-conical shape of the cage and the inability to accurately monitor feed responses on the water surface may lead to feed inefficiencies. This may be particularly so in high-current situations, where the feed may be carried outside of the cage before the fish can ingest the pellets. In land-based tank trials, *S. rivoliana* can attain feed conversion ratios of around 1:1 (dry pellet feed to wet fish produced). In Kona Blue offshore cage array, however, feed conversion ratios are usually around 1.8:1, and can reach 2:1 for some cages. Video cameras are already used to monitor feeding throughout the eight-cage Sea Station grid, but the underwater connections for these cameras are proving problematic. SCUBA diving is needed each time that a connection or cable needs to be replaced, which has become a costly and inefficient task, and leaves feeding in many cages inadequately monitored.

It is therefore, imperative that we identify and validate: (a) an alternative, predator-proof mesh material that represents no entanglement risk to marine mammals; and (b) a more efficient cage design that improves farm operational efficiencies and productivity by affording frequent net cleaning, and reducing the SCUBA diving burden.

Surface accessible cages would also be safer for workers, requiring dramatically less SCUBA diving. (Less dependence on SCUBA also affords the option to hire employees who are not commercially trained divers). Cage cleaning, harvesting, and removal of mortalities could all be accomplished without SCUBA diving. SCUBA diving beyond a maximum depth of 10 metres should be limited, and there should always be direct access to the surface for safety of the diving practices. Ideally, divers will also be able to enter and exit the cage directly from the surface, thereby eliminating the "leakage" of occasional fish through the underwater zippers (as divers enter and exit the cage). This would also remove the presumptive attractant for the bottle-nose dolphins to farm sites.

Kona Blue has already received permit modification approval from the State government to modify the offshore array to deploy larger submersible net pens, each up to 7 000 m^3 volume, which will be able to be largely tended from the surface, similarly to a standard surface pen, and will have Kikkonet walls. These are to be deployed starting in May 2010. These further technological developments should allow open ocean mariculture efficiencies to approach those of surface pens in more protected locations, but with the attendant fish health and environmental benefits from open ocean production. With proof of these efficiencies, then, the capital for industry expansion should become more widely available.

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Challenges for developing emerging economies to engage in off-the-coast and offshore aquaculture: the perspective from a case study

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ABSTRACT

The rapid progress of the Chilean salmon farming industry, its state of the art technology and existing off-the-coast autonomous systems, make this a relevant case study for further exploration of the challenges countries face when moving aquaculture offshore. During the second half of 2007, after more than two decades of impressive growth, the Chilean salmon industry has been facing its worst crisis due to the effects of the Infectious Salmon Anemia (ISA) virus on Atlantic salmon (*Salmo salar*). The harvest declined by 50 percent in 2010 in comparison to 2008. The impact of the ISA can only be seen as the final stage of environmental deterioration and fish health decline which has been evident since 2004 due to high farming concentration, very high farming densities, poor management and highly disease susceptible smolt. After three years of ISA impact, thanks to a number of management measures, there are clear indications that the crisis will be controlled. The re-born industry will have new regulations, a new enforcement system and new voluntary measures. A new production model containing very profound changes will allow to become a future leader in this industry not only in quantitative terms but also qualitative. The industry will increase its proportion in offshore operations, principally in the XI and XII regions. The Chilean experience has left in evidence for countries moving aquaculture off-the-coast and offshore that visionary and focused technology transfer processes are essential for high market potential species, as well as, the existence of well qualified workers and professionals. The assignment of aquaculture areas or zones should consider that such adequate areas for aquaculture (AAA) have to be based on the best oceanographic, climatic and environmental scientific information relevant to local conditions. The industry should take into account that at present there are technologies that make technically and economically feasible farming in more exposed

zones, principally finfish, leaving coastal sites for other uses like shellfish and seaweed farming and artisanal fisheries operations. Besides, enclosed, poor water renewal marine areas, estuaries and lakes should be avoided for intensive farming uses or at least used after a previous evaluation of their carrying capacity under the worst scenario. A zone management system should be emphasized in order to produce in accordance with the carrying capacities of the different water bodies in heterogeneous environments, such as the channels and fjord areas in southern Chile. A logistic model should be established to avoid disease dispersion between farms due to navigation routes and cross contamination in ports which should be well supported by a permanent biosecurity system. The success of an off-the-coast and offshore farming system rests on well-qualified personal able to operate sophisticated new generation farming technologies, well engaged workers, with equitable earnings and benefits and appropriate risk assessment of activities and locations. Overall, a participative and ecosystem governance approach should be considered to guarantee stable and sustainable industry development.

BACKGROUND AND RATIONALE

Due to the rapid expansion of aquaculture worldwide, the demand for more resources such as seeds, feeds, freshwater and inland/coastal space has greatly increased. The search for additional areas to expand and the identification of new farming species to satisfy growing market demand, are forcing entrepreneurs to extend farming activities further off from the coast to offshore where more space is available and competition with other interest groups is currently not as intense.

The development of "off-the-coast" and "offshore" aquaculture" (Table 1) raises a number of biological, spatial, technical, socio-economical, legal and political issues that fall under the consideration of the Food and Agriculture Organization of the United Nations (FAO) and its Member countries. FAO is in the process of collecting global information relating to the potential for off-the-coast and offshore aquaculture which involves the preparation of reviews on specific issues by experts. The current review along with the other technical documents in this proceedings form a global synthesis that culminated in a technical workshop that took place in Orbetello, Italy, in March

TABLE 1
Coastal, off-the-coast and offshore aquaculture definitions used in this review (working definitions agreed with FAO)

	Coastal	Off-the-coast	Offshore
Location/ hydrography	- <500 m from the coast - ≤10 m depth at low tide - within sight - usually sheltered	- 500 m–2 km, - <10 m depth at low tide to ≤50 m - 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, etc.	- Some automated operations, e.g. feeding, monitoring - Professional divers needed for moorings and servicing the cages and nets	- Remote operations, automated feeding, distance monitoring, system function - Highly specialized professional divers and technical teams needed for servicing moorings, cages, nets etc.

2010, that addressed the major components of a global programme for the development of mariculture off-the-coast and offshore.

The present review addresses the economic, technical, legal/political and marketing challenges in the development of existing off-the-coast commercial aquaculture in a developing country. The rapid progress of the Chilean salmon farming industry, its state-of-the-art technology and existing off-the-coast autonomous systems, make Chile a relevant case study for further exploration of the challenges countries face when moving to offshore farming.

THE EVOLUTION OF THE SALMON INDUSTRY IN CHILE: SOCIAL AND ECONOMIC IMPACTS

The industry and its social impact

Commercial Chilean aquaculture is characterized by a highly specialized monoculture systems dominated by salmonid species (Table 2), which in 2008, represented more than 529 000 net export tonnes (82,3 percent of contribution) with a value of US$2 474 573 000 (Selling Freight-on-Board or FOB), 82.3 percent and 88.4 percent, respectively (IFOP, 2009). However, by 1980 salmon farming started very small scale, low technology, low investment, moving in few years to a very specialized and high technology industry.

Southern Chile, especially the X and XI administrative regions (Figure 1) where salmon farming is currently taking place, displayed the country's poorest social and economic indicators in early 1980. Within two decades, and as a result of the rapidly growing salmon industry, poverty indicators had fallen into the same category as Chile's highest performing regions, especially in terms of employment and

FIGURE 1
Salmon sea farming zones (X and XI Regions) and sources of feed producing zones (fish meal/oil and grains)

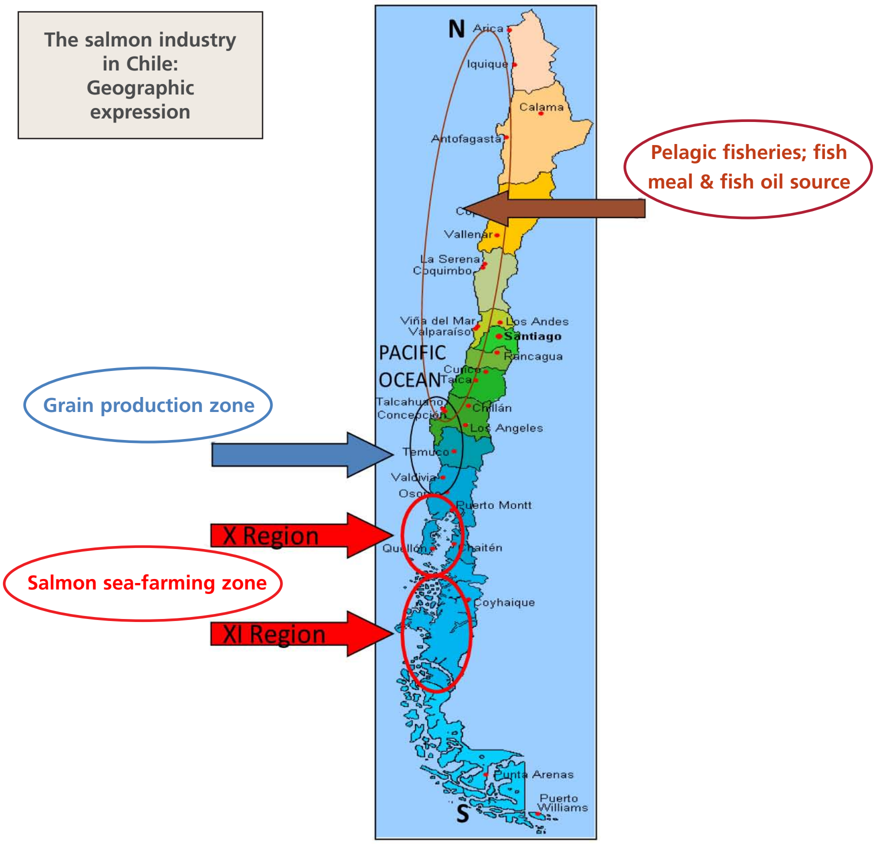


TABLE 2
Chilean aquaculture production 2010 (tonnes)

Species	Total
Haematococcus	12
Huiro (*M. pyrifera*) [Giant kelp]	12
Pelillo (*Gracilaria* spp.) [Gracilaria]	12 150
Spirulina	5
Hirame (*P. olivaceus*) [Olive flounder]	7
Atlantic salmon (*S. salar*)	123 233
Coho salmon (*O. kisutch*) [Pacific salmon]	122 744
Chinook salmon (*O. tshawytscha*) [King salmon]	636
Rainbow trout (*O. mykiss*)	220 244
Turbot (*P. maximus*)	292
Abalon rojo (*H. rufescens*) [Red abalone]	794
Cholga (*A. ater*) [Cholga mussel]	1 736
Chorito (*M. chilensis*) [Chilean blue mussel]	221 522
Choro (*C. chorus*) [Choro mussel]	757
Ostion del Norte (*A. purpuratus*) [Northern scallop]	8 840
Ostra Chilena (*O. chilensis*) [Chilean oyster]	163
Ostra del Pacifico (*C. gigas*) [Pacific oyster]	94
Total algae	**12 179**
Total finfish	**467 156**
Total mollusc	**233 906**
TOTAL	**713 241**

Source: Elaborated based on SERNAPESCA statistics (www.sernapesca.cl).

per capita export. In these same decades, high emigration was replaced by immigration and the poorest segments declined as income per capita increased. The industry was able to offer around 25 000 direct job positions and 20 000 indirect positions up until 2007. Surrounding a nucleus of approximately forty companies, more than 1 200 suppliers, consolidated a natural cluster that has been well documented by different authors (Montero, Maggi and Parra, 2000; Maggi, 2002; Katz, 2004; Agraria Consultores, 2004; Pérez-Aleman, 2005; Torres, 2006; Boston Consulting Group, 2007; Iizuka, 2009).

From 2000 up to 2003 communities with salmon farming industry experienced a larger poverty reduction than the Chilean average, and much more than other communities without salmon farming in the same region (Table 3). The autonomous income of salmon farming within communities has increased by 15 percent, much higher than the country's average of four percent and 10 percent in the whole salmon region (i.e. the X Administrative Region in Chile).

TABLE 3
Variation of social indicators from 2000 to 2003

Variation period 2000–2003	Not salmon related communes (X Region) (%)	Salmon related communes (X Region + Puerto Aysén) (%)	Total country (%)
Poverty	-17	-13	-6
Indigence	-22	-42	-10
Autonomous income	10	15	4
Monetary subsidies	27	23	16

Source: CASEN, 2003.

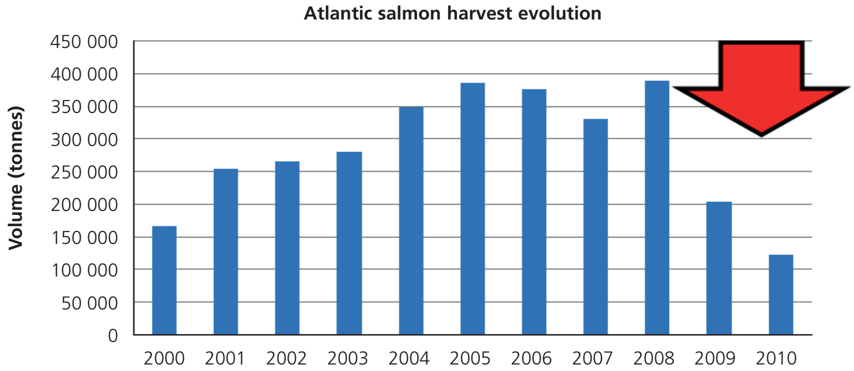
In spite of this accelerated growth, regulations, enforcement systems and research were behind industry development in addition to a low allocation of resources by government. Furthermore the industry did not devote sufficient attention to establishing good links with communities and third parties (such as artisanal fishermen and tourism) sharing common coastal zones and thus in times of difficulty, the sector lacked support from these parties and faced strong criticism.

According to Amtmann and Blanco (2001) there is a strong relationship between agriculture and salmon farming in the southern regions of Chile. It is possible to notice that the depression of one sector is functional to the development of the other and the recent salmon industry crisis illustrates this connection in terms of employment levels. It is also evident that there has been a return to artisanal fishing activities.

The environmental and the sanitary crisis

Since the second half of 2007, after more than two decades of impressive growth, the Chilean salmon industry has been facing its worst crisis due to the effects of the Infectious Salmon Anemia (ISA) on Atlantic salmon (*Salmo salar*). Consequently, the harvest of this species showed a sharp decline in 2009 and 2010 (Figure 2). However, the impact of the ISA can only be seen as the final stage of environmental deterioration and fish health impoverishment which has been evident since 2004. During that period

FIGURE 2
Production evolution of Atlantic salmon (tonnes per year)



Source: SERNAPESCA statistics (www.sernapesca.cl).

biomass at any site and density of sites increased particularly in the coastal areas of the X region and most notably in the central and east coasts of Chiloé Island, where approximately 40 percent of the total salmon production was concentrated.

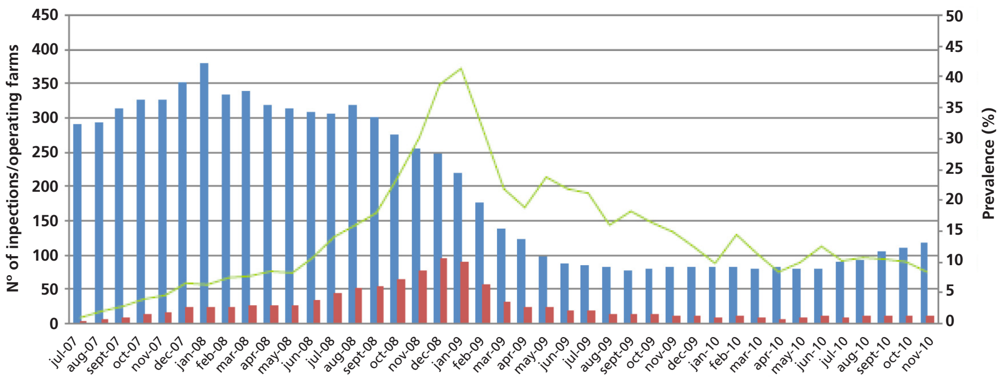
At the end of 2006 a serious increase in the abundance of sea lice (*Caligus rogercresseyi*) became apparent and was most likely due to a combination of higher water salinity, an increase in the concentration of fish farming, condition of the fish and increased parasite resistance to the only approved drug for years in Chile, i.e. emamectine benzoate. Sea lice spread rapidly through the X and XI regions reaching high levels of infestation, in some cases thirty to fifty parasites per fish. Due to resistance development, the drug used proved to be ineffective. Fish were stressed, immunologically depressed and externally damaged, all of which were key factors contributing to the rapid penetration of opportunistic pathogens.

In July 2007, during efforts to control the sea lice epidemic, Marine Harvest Chile (MHC) informed of an ISAv finding in Atlantic salmon pertaining to a site in central Chiloé after first confirming it with local and foreign reference laboratories. Only a few days later other sites were reported to present ISAv outbreaks and from that point on the virus spread rapidly through the X, XI and XII regions despite rapid contingency measures implemented by the government and the voluntary measures agreed to by the salmon companies.

From the first detection of the virus MHC together with Chilean laboratory Biovac and Dr Fred Kibenge's laboratory on Prince Edward Island have been developing an epidemiologic study which has recently shown that the Chilean ISAv is genetically unique, although similar, to an ISAv reported in Norway in 1996. Using the software program, Backtrack, it was estimated that the virus was present in Chile as early as 1996, and suffered a strong diversification around 2005. The virus found in the first reported case by MHC in July 2007 was not the oldest strain of the ISA viruses existing in Chile at that point. This suggests that the virus had been present in the Chilean environment for several years and due to its low prevalence and lack of adequate detection techniques mortality events could not be linked to it.

At present, sea lice is under control due to a successful control plan and damages found on the fish have decreased dramatically. In addition, total biomass and densities have rapidly declined. A number of new regulations and volunteer measures are in place, which support zone management programmes; strict eggs import control and complete biosecurity measures, initiating the process to control ISA (Figure 3). These regulations, together with drastic changes are resulting in a new production model for the industry. Although a biological improvement is becoming apparent, the consolidation of industry change demands law adjustments and company investment, which are presently materializing.

FIGURE 3
ISA trend in Atlantic salmon. The graph shows the numbers of ISA inspections and prevalence percentage (green line) in operating farms (blue bar), positive farms (red bar), between July 2007 to November 2010



Source: Technical Report of the Specific Health Surveillance and Control Program of ISA virus 2008–2010. www.sernapesca.cl

The crisis will be controlled and the change in production ratios started in the second semester of 2009 while stocking reactivation will start in 2010. Therefore a change in annual production trend can be expected in 2011. The new industry will have new regulations, new enforcement system and new voluntary measures. Finally a new production model containing profound changes will allow Chile to become a future leader in this industry not only in quantitative terms but also qualitative. Knowledge about the environment, its dynamics and carrying capacity will be fundamental to the new industry's success. Without these elements Chile will not be able to manage the sanitary contingencies in the long-term and it will face the risk of new crisis as severe as the present one.

TECHNOLOGICAL DEVELOPMENT: THE BIRTH AND GROWTH OF AN AQUACULTURE INDUSTRY THAT MUST MOVE OFF-THE-COAST

Technology and industry evolution

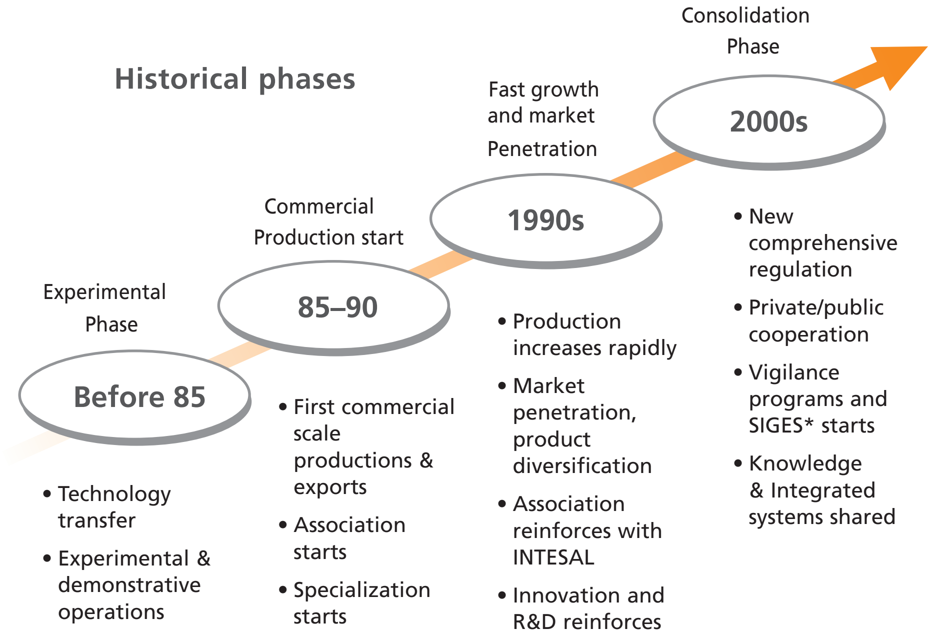
The salmon farming industry in started at the end of the 1970s after some initial management and legal problems. Since then "Fundación Chile" has played a vital role in importing and transferring technology for intensive salmon production in captivity which triggered the new industry based in the X region (Los Lagos).

Basic technology was imported principally from Canada, United States of America, United Kingdom and Norway. Hatchery equipment and cage designs were based on models being applied in those countries with minor adaptations in some cases to Chilean necessities. Eggs were also imported from those countries. It was clear that Chile had the natural conditions to develop a very competitive industry together with professionals and technicians well prepared to take position in the emerging industry.

The evolution of the industry can be seen in Figure 4 which shows the different stages of development up until now. It is important to mention that at the beginning of the experimental phase sea cages were manufactured *in situ* and gradually some imported cages were introduced from the northern hemisphere.

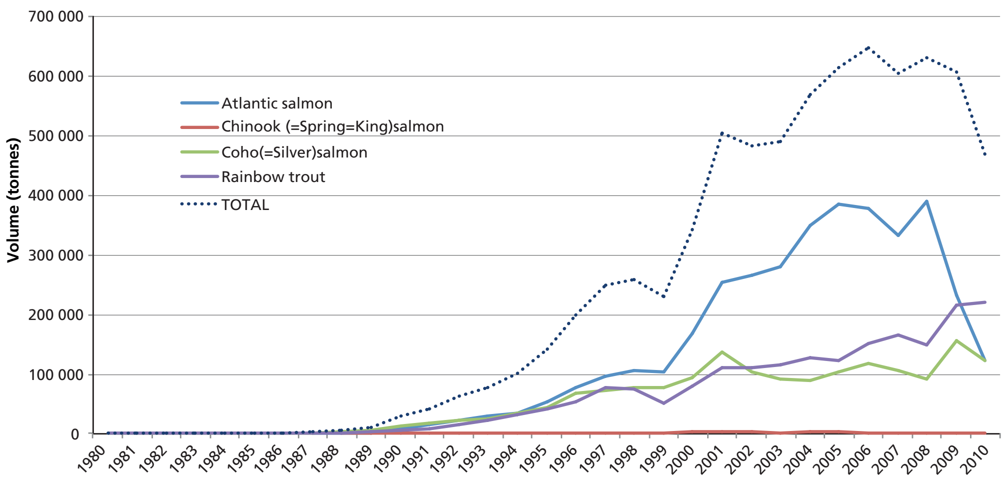
It is also important to mention that in the beginning of the industry and up to 1995, three species; rainbow trout (*Oncorhynchus mykiss*) coho salmon (*Oncorhynchus kisutch*) and Atlantic salmon (*Salmo salar*) shared the production volume. After 2000 Atlantic salmon became the dominant species (Figure 5) due to its highest market demand. The salmon disease crisis since 2008 did not cause a sharp decrease in total salmonid production in Chile until 2010 also due to the increase in trout and coho salmon production.

FIGURE 4
Salmon industry evolution phases in Chile



*SIGES: Sistema integrado de gestión.

FIGURE 5
Evolution of production of the farmed species of salmon and trout in Chile



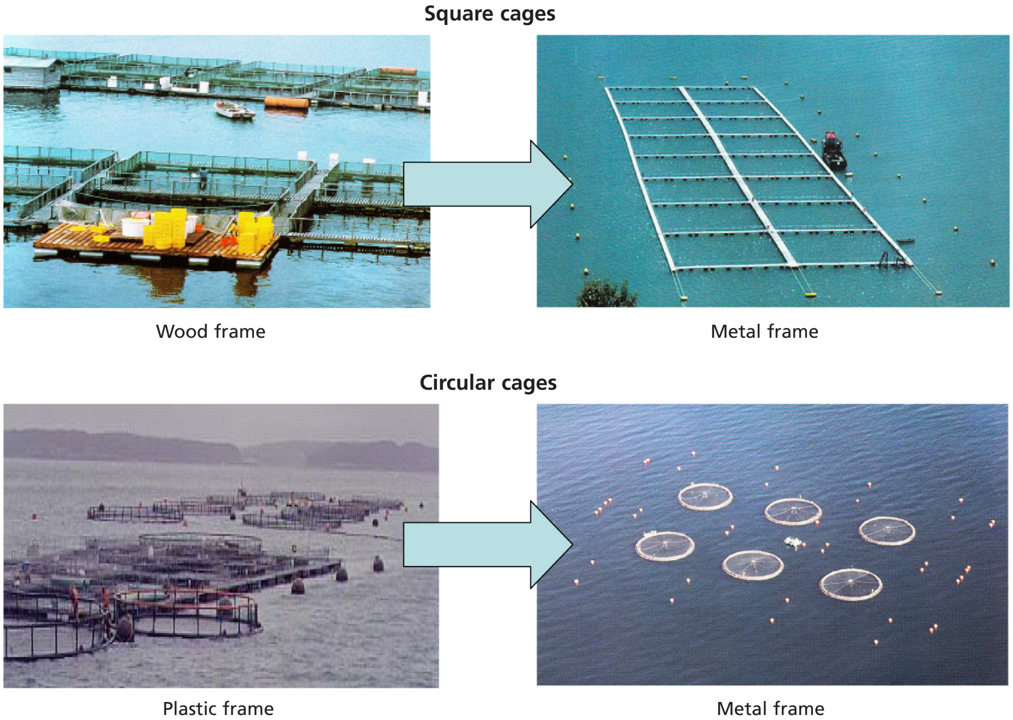
Source: Global dataset of aquaculture production (quantity and value) 1950–2010. Released in March 2012, by Fisheries and Aquaculture Statistics and Information Service, FAO.

Farming environment and equipment

Enclosed coastal waters were preferred for the initial operations of sea cages settlement, all of them within the adequate areas for aquaculture (AAA) range or areas where aquaculture was authorized in the sea. Protected bays and fjords were utilized to mitigate impact by strong, predominantly north western winds, as well as, short but intense periods of southern winds during the spring and summer months. Usually these sites did not exceed 20–30 m in depth and had low water renewal. At that stage, all salmon cage frames and farm set up in the emerging Chilean industry were made of wood and their fragility emphasized the need to protect them from severe weather

FIGURE 6

Different types of cages used in seawater conditions in the Chilean salmon industry representing technology evolution. Top left: early 1980s; top right: represents late 1980s; bottom left: mid-1990s; and bottom right: mid-2000s



conditions. Sites normally had one or two modules of 10 square cages, 10 × 10 × 10 m or 15 × 15 × 15 m in dimension. With the exception of some "coastal" experimental units most of the cages installed in the sea for salmon growout were, according to the definition used in the present document (Table 1) "off-the-coast" as it was not viable to settle these cages in locations less than 10 m in depth ("coastal" farming) due to sediment re-suspension and wave effects.

By the end of the 1980s, square metal-framed cages were introduced allowing farms to be settled in more exposed areas which could be classified as further off the coast centers. Favoring the colonization of more exposed areas, the circular polyethylene and metal-framed cages were also introduced in the 1990s (Figure 6).

At present all types of cage models are produced by national and foreign companies in Chile. Only a small fraction is still imported, especially the circular models highly suitable for exposed zones. Table 4 summarizes cages characteristics and evolution.

Most recent sea cage structure innovation includes polyethylene nets followed by copper based nets, a recent innovation in Chile. Polyethylene nets are being used in commercial operations in the XI region with satisfactory results while copper nets are still in the experimental and validation phase. Other innovations in the making include developing submerged feeders and innovating present pen systems to improve vertical cage movement. New submerged cages, developed by a company in Israel, are also being offered to Chile.

Farming sites and equipment trends: what to expect in the future

Further development of salmon farming in Chile will have to continue the trend of moving off-the-coast and offshore, both due to the current diseases crisis, but also to allow expansion and to avoid environmental impacts and conflicts with other users of channels and fjords.

TABLE 4
Square and circular cages – characteristics and evolution

Square cages	1993	1995	1998	2002	2006	2010
Side (m)	12	15	20	30	30	30
Depth (m)	9	12	15	15	15	15
Volume (m³)	1 296	2 700	6 000	13 500	13 500	13 500
N° Fish (avg)/site	300 000	500 000	700 000	900 000	1 000 000	1 200 000
N° Fish/cage	7 500	13 889	25 000	45 000	50 000	85 714
N° Cage/site	40	36	28	20	20	14
N° Fish/m³	231	185	117	67	74	89
N° modules	2	2	2	2	2	1
Depth of sites trend	15–30	–	–	30–50	–	40–80
Estimated production/site (mt)	1 200	–	–	3 500	–	4 500
Circular cages	**1993**	**1995**	**1998**	**2002**	**2006**	**2010**
Diameter (m)	–	24,5	30	31,6	35,8	34,1
Depth (m)	–	15,9	18	18	16,5	16,8
Volume (m³)	–	7 496	12 723	14 099	16 562	15 334
N° Fish (avg)/site	–	200 000	700 000	1 000 000	1 200 000	1 800 000
N° Fish/cage	–	20 000	35 000	35 714	30 000	45 000
N° Cage/site	–	10	20	28	40	40
N° Fish/ m³	–	27	55	71	72	117
N° modules	–	1	1	2	2	2
Depth of sites (m)	–	20–40	–	30–50	–	50–100
Estimated production/site (mt)	0	–	–	3 500	–	6 700

Note: The circular cage diameter and depth is representative of weighted average values of specified years.

- No further salmon sites will be licensed in the X region (already under enforcement) and stricter control and requirements will be established in the XI and XII regions.
- A review of existing authorized aquaculture areas will take place with the view of expanding them and allowing the relocation of some "coastal" salmon farming sites. This is currently under discussion based on new law adjustments and will involve abandoning shallow and enclosed bays where water dynamic is poor for more exposed sites, in other words a movement further off-the-coast and possibly towards offshore can be expected in Chilean salmon farming. Offshore aquaculture areas are not expected in the next ten years, given the rough conditions of the Pacific coast, but certainly more exposed zones in the canals and interior waters will be colonized.
- A review of established salmon neighborhoods will take into consideration environmental zones or waterbodies. There is a wide consensus that the "aquaculture neighborhoods" currently in place do not reflect homogeneous zones in environmental terms, but it is accepted that this is a good beginning and that a review based on the best scientific information including elements of carrying capacity is going to be necessary. Future assignment of salmon environmental zones should consider specific management plans for each in order to effectively protect biodiversity and ecosystem services.
- Different companies will try to concentrate their farms in discrete zones by exchanging licenses, and also companies will be able to merge some of their own licenses in order to create more distance between their site clusters and others. This option has been considered in the discussion of the new law.
- New ports will be established to serve specific aquaculture zones avoiding complex navigation tracks that increase the risk of disease dispersion. In addition, area segregation in ports will be established and ports for specific and compatible uses are expected.

FIGURE 7

Examples of submersible pens designs used for offshore mariculture. Left image: Cates International Inc. system; right image: AquaPod Cage

COURTESY OF DANIEL BENETTI

COURTESY OF DANIEL BENETTI

- Navigation control of aquaculture supplier boats will be established making it possible to detect deviations or use of unauthorized routes.
- Mortality will be stored in hermetic containers and immediately neutralized out of the sites, to avoid the risk of disease dispersion and contamination.
- Harvesting with biosecure well-boats will be increased to avoid sanitary risks and improve final product quality. Several systems are being evaluated based on this approach.
- As a result, logistic as well as investment costs will increase, but it is expected that they will be compensated with higher productivity and less risk of collapse due to environmental or sanitary disruptions.

In short, the industry will increase its proportion of operations further off-the-coast and offshore, mainly in the XI and XII regions and initially, it is likely to depend on foreign supplies such as Subflex-Navtec (Israel), Open Ocean System Inc. (Canada), Ocean Farm Technologies Inc. (USA) and Aqualine (Norway), including submersible sea cages type (Figure 7). At the same time, adjustments to present off-the-coast sea cages will be made to move them within the water column itself in conjunction with the development of feeders and extractors for deceased fish. In parallel, new copper and plastic based net materials will diminish the biofouling impact and sanitary risks on sites. In general, Chilean companies are not considered innovative and tend to import technologies from overseas (Aqua, 2007) but this is changing out of necessity to the present environmental/sanitary crisis.

VALUE CHAIN COSTS, STRUCTURE AND SOURCES OF FINANCING

Value chain and cost structure

Table 5 puts into perspective the contributions of the different cluster components of the salmon value chain in Chile over time, illustrating the three farmed species: Atlantic salmon, rainbow trout and Coho salmon for 2002, 2004 and 2008.

It is interesting to note the following trends in the cost structure over time:

- Sanitary and environmental pressures have increased production costs for fish farming. Therefore farming conditions and biosecurity measures have increased. In addition, feeding costs and higher mortality rates increased from 2004 to 2008.
- Higher fuel costs have in turn increased internal transport costs.
- Consolidation of the industry within its target markets has decreased administration and sales costs.
- Processing costs have also diminished due to higher plant efficiency.

TABLE 5
Specific weight of value chain components over time. This analysis does not include export costs, distribution costs and margin in the target markets

	2002 [1]		2004 [2]		2008 [3]	
Phases, subsectors and components	**US$ (millions)**	**Value (%)**	**US$ (millions)**	**Value (%)**	**US$ (millions)**	**Value (%)**
Hatchery and smolt production	**49**	**5.0**	**50**	**3.3**	**156**	**6.30**
Growout/seawater production	**535**	**55.0**	**830**	**55.30**	**1 508**	**61.00**
Fish Feed	341	35.0	500	33.3	965	39.0
Labour	117	12.0	120	8.0	135	5.5
Feed additives (pigments, vitamins, minerals)	29	3.0	120	8.0	198	8.0
Health	10	1.0	40	7.0	109	4.4
Cage structure and nets	29	3.0	20	1.3	30	1.2
Diving services	5	0.5	15	1.0	12	0.5
Other inputs and services	5	0.5	15	1.0	59	2.4
Processing plant	**146**	**15.0**	**290**	**19.3**	**327**	**13.20**
Labour	107	11.0	180	12.0	223	9.0
Packaging	19	2.0	60	4.0	74	3.0
Other expenditures	19	2.0	50	3.3	30	1.2
Domestic transport	**39**	**4.0**	**80**	**5.3**	**143**	**5.8**
Maritime freight	19	2.0	40	2.7	72	2.9
Inland freight	19	2.0	40	2.7	72	2.9
Selling and administrative expenses	**68**	**7.0**	**80**	**4.7**	**92**	**3.7**
Financial cost and profit	**136**	**14.0**	**40**	**12.0**	**247**	**10.0**
TOTAL	**973**	**100.0**	**1 500**	**100**	**2 474**	**100**

[1] *Source:* Maggi, 2002.
[2] *Source:* CORFO, Región de Los Lagos, 2004.
[3] Estimates based on information collected and/or provided by the Instituto de Fomento Pesquero (2009) and INTESAL.

Projections for the next five years:

- Relative weight of freshwater production will have a tendency to increase by approximately 10 percent due to more frequent use of recirculation systems to produce smolt on land and the need for larger fish to be stocked in the sea.
- The relative cost of production in the sea should drop back to 55 percent due to the higher smolt quality and size and also due to the effects of biosanitary measures and implemented logistics which will reduce mortality and increase efficiency.
- Processing should stabilize at about 13 percent and internal transport at about 6 percent.
- The need to re-conquer Altantic salmon markets after the crisis will raise the cost of administration and sales to around 5 percent and both the financial cost and profit margin by 11–12 percent.

Financing sources

Investment in cages, logistics, landing sites, boats, etc., is strictly financed by producers. They are able to obtain bank credits but like any other private agent in the country they need to comply with contractual obligations.

After evaluating the viability of the industry and companies, banks have renegotiated the debt for most of them. In parallel, banks have pushed for tighter regulations and practices that provide better management of sanitary/environmental risk. Despite debt renegotiation, credits were almost suspended motivating some companies to try to get financing from the stock market after environmental/sanitary industry improvement.

Due to these circumstances the Chilean Government has instigated co-financing and endorsement for company projects directed at developing improvements in sanitary/environmental management. Although these aids are being used to a certain extent, it is crucial that the new law meets with approval and fulfills many obligations that will restore confidence within financial systems and potential new investors.

Additionally, some Norwegian companies, using co-financing, are offering sea cages to Chilean investors. These co-financial instruments are based on Norwegian funds promoting technology exports to other countries.

Nowadays, most sea cage components are produced in Chile. However, it is still optional to import some special parts and supplies from different countries such as ropes from Greece or marine lights from Australia. Nevertheless, over time, local suppliers have been able to incorporate the latest technology to their local offer and have developed a variety of elements and parts including automatic feeders, electronic control equipment and related software.

The design of the above elements is specific to the requirements of individual Chilean companies and takes into consideration environmental control needs. It is currently possible to find a wide variety of high quality services and products in Chile that are also actively exported with the exception of large circular cages, 100 m in diameter, for offshore conditions such as it was planned by Aqualine for the Tripanko project, south of Chiloé Island.

Local suppliers are able to supply amongst other, environmental site evaluation and characterization, site design and mooring, feeding systems and automatic control installation, all to an exceptionally high standard. Such supply services, highly specialized are also very sensitive to fluctuations of the salmon production and markets and therefore suffered from the Atlantic salmon crisis. However, the more recent development of finfish cage culture in other countries in the region, e.g. Brazil, Ecuador and Peru has created a market for such products and services.

SITE SELECTION AND ZONING

Zoning and scientific knowledge

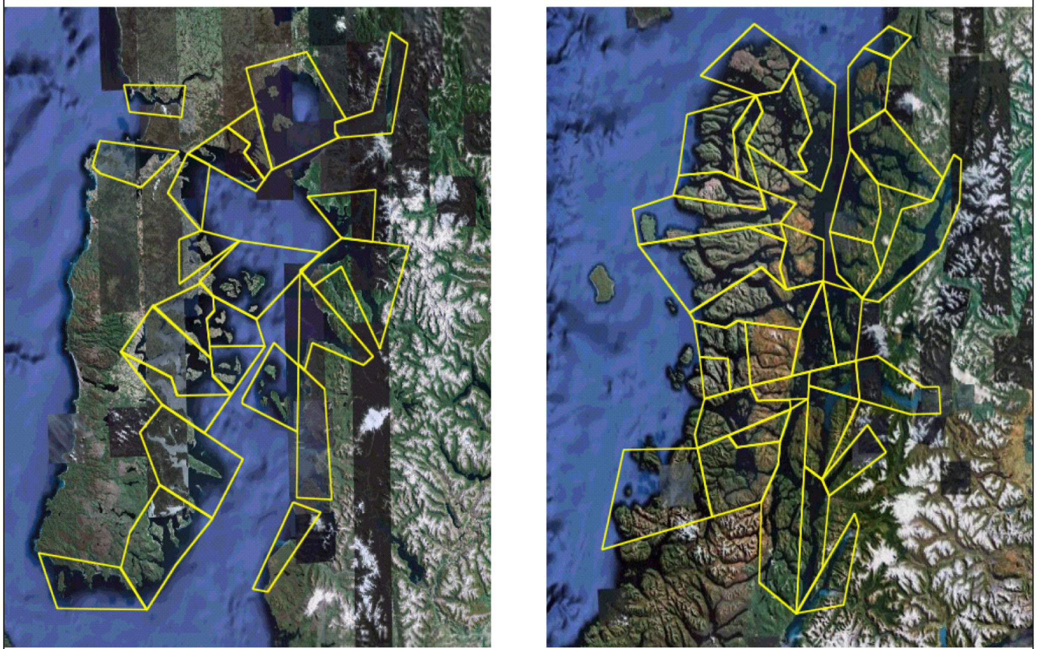
Since 1980, salmon Farming has been forced to comply with regulations regarding aquaculture siting only in allowed areas (or adequate areas for aquaculture – AAA). This measure, as well as the initial search for protected areas, proximity to basic services such as ports, lodging, etc., has produced a high level of farms concentration in some areas such as central Chiloé Island. Out of necessity, salmon farms had also occupied areas that are not naturally suitable for farming, but more favorable for mussels, abalone and algae farming. As a result of such siting, conflict with artisanal fisheries has often arisen, given the proximity to natural banks, ports of operation and navigation routes.

At that time, the lack of knowledge about these zones enhanced the problems described above. However, current scientific and technical information has altered the perception and demands for such zones. The situation became remarkably difficult in the X region where it was necessary to close the authorization of new licenses. Concessions in the XI and XII regions will also be frozen for the next few years until a review of all the zones can be completed (Figure 8).

Farm settlement regulations

In spite of the above difficulties, site selection is based on environmental, sanitary and logistic criteria. Salmon farming companies use external professionals and experts to make a site evaluation and then develop a type of environmental impact assessment known as "environmental declaration" (ED) as current environmental regulations, do not require a full environmental impact assessment (EIA). The ED is presented when applying for a farming area license. A complete breakdown needs to be presented specifying projected production, species and technology to be utilized. This documentation requires approval by all organizations and institutions involved, amongst others: fisheries and aquaculture authorities, regional and local governments, environmental authorities, maritime authority, sanitary authorities, artisan fishery unions, research institutes, tourism authorities, First Nation organizations, and

FIGURE 8
Salmon industry neighborhoods located in the X and XI regions, Chile



X Region XI Region

Source: Sernapesca (2001).

others, all of which are consulted through a unique window process. The regional environmental authority makes the final decision to approve or deny authorization or suggest adjustments. The project is then required to demonstrate that it is operating in compliance with the requirements established in terms of impact on sediments and benthos (Environmental Regulation for Aquaculture [RAMA]).

Current regulations, request all projects to participate in the zone management programme respecting fallow periods established for the area, smolt entrance period and sea lice treatment coordination, among some of the principal measures.

Zoning and logistics

The main challenges in the future will be to review salmon and aquaculture zones and initiate a long-term integrated management plan of coastal zones considering that most southern Chile fjords and channels are very deep and exposed waterbodies. Focused research will need to be conducted thus providing essential support for each zone. This needs to be a public-private effort of maximum urgency. At the same time, the government should develop a strong and efficient legal system that will support the management and sustainable development of the salmon industry. Collaboration from the private sector via voluntary agreements and special measures is also considered essential.

The XI and XII regions of Chile have enormous potential for aquaculture, but to realize this potential in a harmonious and sustainable way, it is essential that this be done in coordination with a logistic plan containing the elements indicated above. There is wide consensus on this.

Currently there are not enough airports to transport workers to pickup points where they can be taken by boats to farms. Furthermore, existing air transportation is unsafe and inadequate, made worse by the region's stormy conditions. There is a demand for increased and higher quality housing plans for workers and transportation services to move products and storage materials within remote areas.

All the conditions above are essential for any off-the-coast and offshore aquaculture to develop in more remote areas.

CHANGES ASSOCIATED TO THE NEW PRODUCTION MODEL

Smolt production

The emerging production model requires the industry to concentrate the freshwater phase entirely on land-based facilities. At the moment this is a voluntary measure agreed to by the salmon farmers association, SalmonChile, and it is likely that over the next two years salmon broodstock will be maintained only in tanks or in special areas in the sea. In addition, the smoltification process will be completed in on-land tank facilities and the smolt will more than likely be sent to the sea when they reach approximately 300 g.

There are at least three large projects close to completion developing land-based smolt production facilities starting with broodstock. This trend is congruent with the intensive control of imported eggs. Audits of suppliers' facilities are already being applied. In addition, there are three smoltification units on land will avoid this intermediate phase in lakes and/or estuaries.

Investment in facilities of this kind ranges from US$6 million (smoltification units) to US$15 million in the case of freshwater production based entirely on land facilities. In summary, it is expected that smoltification units in lakes and estuaries will decrease and there will be more land based operations with the tendency to produce the entire freshwater cycle on land. Although this will represent higher investment costs it is expected to lead to higher quality smolt showing improved performance and ability to resist the challenges in the sea.

Seawater phase

Under the newly established zoning model with neighborhoods, companies and private owners will have to coordinate and manage production within the criteria of the zone management programme. Each zone will demand, in a coordinated manner, services such as ports, navigation routes and mortality transport and management (in some cases under joint contracts), as well as, harvesting.

It is expected that each zone will have its own administration and information sources, such as an environmental and sanitary observatory, and there should be indicators in place to evaluate the efficacy of the measures for each zone.

The quality of the smolt should be checked before sending them to seawater and in addition they should be vaccinated against diseases likely to be present in the next phase.

Processing plants

Along with improved harvesting methods and fish harvesting transport, it is expected that coastal "waiting cages" to receive the harvested fish will be eliminated and replaced by tanks on land. From these tanks fish will be transported to processing plants.

Waste treatment, including disinfection, is already mandatory in processing plants as well as hatcheries.

Transport

Improvements in the transport of live fish from one phase to the other are expected and will diminish fish stress levels and create better transition conditions thus reducing the shock caused by movement between containers.

Other products and services

A number of new products and services that illustrate the tendencies of the industry are being developed. Amongst these: oceanographic and epidemiological services, bioassay units, innovation in farming units (sea cages), a diversity of biosecurity (disinfection) services, ports with segregation of areas, closed well-boats, live harvest well-boats, silage mortality containers; mortality extractors, submerged feeders, new net materials, net cleaners *in situ*.

In general, all the measures described above should be considered when moving aquaculture further off-the-coast in order to make the production systems more efficient, less energy demanding, more biosecure (e.g. by coordinated transport) and more environmental friendly.

CONCLUSIONS

- Salmon farming technology was transferred and adapted to Chile through a fast and effective process initially lead by public-private institution promoting production technology and development, i.e. Fundación Chile, at the end of the 1970s.
- Some operations were initially "coastal" although most of them corresponded with off-the-coast type (Table 1) or quickly moved off the coast due to the requirements for salmon farming and to increase operation size.
- In spite of the range of area available for salmon farming, there was nevertheless a high concentration of fish farms in areas where companies were able to find ports and on-land services more easily available, such as in central Chiloé Island.
- Salmon farming operations in the sea were forced to be spatially concentrated due to the regulations of the AAA and proximity of services.
- Most of the equipment, products and services originally imported from abroad began to be produced in Chile which avoided high import costs. A "true cluster" was then developed in the south of the country with around forty producers and 1 200 suppliers from which around 500 depend fundamentally on the salmon industry. Several universities and research and development centers were established in the X and XI region. As a result, the salmon farming produced an important spillover benefit with relevant social and economic consequences.
- Both X and XI regions were positively impacted by the industry in social terms and they moved from being areas with the highest rates of unemployment in the country to areas having the lowest unemployment rates in twenty years. In fact, these regions presented the highest rates of improvement in terms of poverty and extreme poverty reduction. Emigration changed to migration in less than two decades as a large number of people and businesses moved to these regions in search of employment within the industry and related servicing.
- The economy of both regions relied heavily on the industry which resulted in more than 80 percent of exportation. It sustained job positions and thus replaced agriculture industry in this regard. More than 25 000 direct employment positions and more than 20 000 indirect positions were produced by the salmon industry in the X and XI regions.
- When the sanitary/environmental crisis emerged in the second semester of 2007, a decline of social indicators became rapidly evident as more than 15 000 job positions were lost in less than two years and salmon production reduced by 30 percent during 2009.
- The rapid reaction of the government as well as the industry has allowed for the first signs of recovery during the second semester of 2009 and, as a result, a change in the production tendency can be expected from 2011 onwards.
- The crisis has lead to heavy modifications in regulations, enforcement systems, production model, Research and Development (R&D) and innovation. As a consequence new licenses within the X region have been suspended, and in the XI and XII regions delayed. Changes in regulation will push for reduction of biomass load per area, and increased distance between farms, establishing a zone management programme and a set of biosecurity measures.

- Fish farms will be encouraged to move to more exposed waters increasing the number of offshore sites which will rely on foreign cage technology in the beginning particularly large 100 m in diameter cages that will increase distances between neighborhoods. Most coastal licenses will probably be changed for others in more exposed waters releasing the coastal licences for third party coastal users such as small aquaculture producers (mussels, abalone, seaweed, etc.) and artisanal fisheries sites and logistics.
- This situation has revealed the need to develop comprehensive, integrated coastal and "off-the-coast" management zone plans taking into consideration all parties that use the zone from the very onset. At the same time it is evident that any zone management plan of aquaculture activities has to bear in mind the carrying capacity or indirect indicators reported by independent third party entities. This is needed even if the industry moves further offshore. Also, in the case of sanitary/environmental zoning, the government has to play a leading role, inviting all parties to express their opinions and views but taking the final decision with regards to course of action. The worse scenario in the middle of a crisis is inaction.
- The Chilean salmon farming model will change dramatically and this process is already underway. As a result, freshwater production will be developed entirely in fully controlled mostly recirculation on-land facilities and seawater production in environmental zones with enough separation between farms and between zones to minimizing sanitary and environmental risks. A clear increase in the proportion of offshore sites will be evident, particularly far off-the-coast in the highly dynamic channels and fjords of the XI and XII regions.
- It is clear that this production activity should developed in off-the-coast and offshore sites and supported by a logistic master plan that will allow the sustainable colonization of remote areas, taking care not only of business efficiency and fish welfare, but also of the quality of life of workers who have to move to remote areas for considerable periods of time.

LESSONS AND EXPERIENCES FOR COUNTRIES MOVING TOWARDS OFF-THE-COAST/OFFSHORE AQUACULTURE

Based on the Chilean salmon farming experience described above, it is possible to summarize the following lessons and experiences for countries moving towards off-the-coast and offshore:

- **Authorized areas for aquaculture settlement**
  Adequate areas for aquaculture (AAA) should be established (or updated) based in the best scientific information with regards to oceanographic, climatic and local environmental conditions, integrating data and knowledge and presenting it for open discussion that will enable an informed decision process. The AAA plan initially developed in Chile did not favour off-the-coast and offshore expansion and, on the contrary, it caused the initial high concentration of farms especially in the X region.

- **Flexibility of the adequate areas for aquaculture**
  AAA regulations have to be somewhat flexible in order to recommend adjustments in the system based on new scientific evidence technologies while establishing an eventual compensation system for those licenses that may become affected by the new measures adopted.

  In a higher flexibility of the license system is currently being considered. This would allow relocating coastal salmon licenses to more exposed zones, to merge licenses and also to exchange them. These measures will benefit a general movement of salmon farming to more exposed areas and reduce geographical concentration of farms.

- **Exclusion of sensitive zones (or precautionary use)**
  Enclosed, low water renewal marine areas, estuaries and lakes should be avoided for intensive fish farming or at least used with a previous evaluation of their carrying capacity under the worst case scenario.

  More exposed sites (off-the-coast and offshore) demonstrated in the recent ISA virus crisis in Chile to be more resistant to disease outbreaks.

- **Qualified human resources and basic equipment access**
  The success of an off-the-coast and offshore aquaculture systems rest on qualified personal able to operate sophisticated systems, like automatic feeding systems, monitoring and interpretation of environmental variables, submerged camera control, programme and monitor complex logistic operations like feed supply and harvest operations. At the same time these more exposed systems require high quality and resistant cages and access to supporting floating units (floating pontoons) to store feed, other raw materials and equipment as well as to accommodate the site team (Chile has reached an important development in this field and presently it is exporting these units to other salmon producer countries).

  Proper investments are needed in technical training both at management and production levels. Adequately addressing capacity building can be a key element in increasing the direct and indirect impacts of off-the-coast and offshore aquaculture through the provision of jobs and associative services.

  Countries should always ensure that aquaculture is not only environmentally safe, but that it also benefits society by addressing the needs and expectations of the broader society and stakeholders. This is particularly relevant when cage culture is using aquatic environments, normally considered under most regulations as a "common resource".

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FAO FISHERIES AND AQUACULTURE PROCEEDINGS 24

Expanding mariculture farther offshore

Technical, environmental, spatial and governance challenges

FAO Technical Workshop
22–25 March 2010
Orbetello, Italy

This document contains the proceedings of the technical workshop entitled “Expanding mariculture farther offshore: technical, environmental, spatial and governance challenges” held from 22 to 25 March 2010, in Orbetello, Italy, and organized by the Aquaculture Branch of the Fisheries and Aquaculture Department of the Food and Agriculture Organization of the United Nations (FAO). The objective of this workshop was to discuss the growing need to transfer land-based and coastal aquaculture production systems farther off the coast and provide recommendations for action to FAO, governments and the private sector. Offshore mariculture is likely to offer significant opportunities for food production and development to many coastal countries, especially in regions where the availability of land, nearshore space and freshwater are limited resources. The workshop report highlights the major opportunities and challenges for a sustainable mariculture industry to grow and further expand off the coast. Furthermore, it recommended that FAO should provide a forum through which the potential importance of the sea in future food production can be communicated to the public and specific groups of stakeholders and to support FAO Members and industry in the development needed to expand mariculture to offshore locations. This publication is organized in two parts. The proceedings include the workshop report, and an accompanying CD–ROM containing six reviews covering technical, environmental, economic and marketing, policy and governance issues, and two case studies on highfin amberjack (*Seriola rivoliana*) offshore farming in Hawaii (the United States of America) and one on salmon farming in Chile.