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Site selection and carrying capacities for inland and coastal aquaculture

FAO/Institute of Aquaculture, University of Stirling, Expert Workshop
6–8 December 2010
Stirling, the United Kingdom of Great Britain and Northern Ireland

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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 Workshop on Site Selection and Carrying Capacities for Inland and Coastal Aquaculture convened at the Institute of Aquaculture, University of Stirling, the United Kingdom of Great Britain and Northern Ireland, from 6–8 December 2010.

The workshop was attended by 20 internationally renowned experts from 13 countries (the Arab Republic of Egypt, Canada, the Federative Republic of Brazil, the Hellenic Republic, the Kingdom of Norway, the People's Republic of China, the Portuguese Republic, the Republic of Chile, the Republic of Ghana, the Republic of South Africa, the United Kingdom of Great Britain and Northern Ireland, the United Mexican States and the United States of America), representing the private sector, industry, academia, government, research organizations and FAO.

The workshop was jointly organized by the Sustainable Aquaculture Group, Institute of Aquaculture, University of Stirling, and the Aquaculture Branch of the FAO Fisheries and Aquaculture Department through a collaboration agreement.

The main purpose of this document is to provide guidance to developing countries on the process of aquaculture site selection and carrying capacity to improve the sustainability of aquaculture.

This technical workshop constitutes the first of a series of workshops and activities addressing different issues to help implement the ecosystem approach to aquaculture (EAA). The intended audience for this publication consists of professionals in the fisheries sector at managerial and technical levels in government service, in international organizations and in the aquaculture industry.

The workshop report and the first global review entitled "Carrying capacities and site selection within the ecosystem approach to aquaculture" have been edited by FAO. However, all the other reviews have been reproduced as submitted.

Abstract

An FAO-sponsored Expert Workshop on Site Selection and Carrying Capacities for Inland and Coastal Aquaculture was held at the Institute of Aquaculture, University of Stirling, the United Kingdom of Great Britain and Northern Ireland, in December 2010. The workshop was attended by 20 internationally recognized experts, including two staff members of FAO, and covered a number of relevant core topics and represented aquaculture in different regions of the world. Expertise within the group included the academic, regulatory and consultative sectors of the industry, giving a wide perspective of views on the core topics.

Seven global reviews and ten regional reviews on site selection and carrying capacity encompassing inland aquaculture and coastal aquaculture were presented and discussed at the workshop. Supplementary inputs were provided by the experts who were unable to attend the workshop for the reviews on "Environmental Impact, Site Selection and Carrying Capacity Estimation for Small-scale Aquaculture in Asia" and "Guidelines for Aquaculture Site Selection and Carrying Capacity for Inland and Coastal Aquaculture in Mid- and Northern Europe".

Definitions of carrying capacity appropriate for different types of aquaculture were discussed and agreed based upon four categories: physical, production, ecological and social.

The range and capability of modelling tools, including spatial tools, available for addressing these capacities were discussed. The prioritization and sequence for addressing site selection and the different categories of carrying capacity were considered in detail in terms of both regional or national priorities and site-specific considerations.

Two major outcomes have been developed from the workshop: (i) a comprehensive record of the workshop proceedings (this document), which includes global and regional reviews and a summary of major findings and recommendations; and (ii) a set of guidelines for addressing site selection and carrying capacity in the context of the framework of the ecosystem approach to aquaculture (EAA), including summaries of the key findings and recommendations for aquaculture site selection and carrying capacity with an EAA perspective. Recommendations were made for promotion of these concepts and approaches by FAO.

This publication is organized in two parts. One part contains the workshop report and the first global review entitled "Carrying capacities and site selection within the ecosystem approach to aquaculture", while the second part is the full document. The latter part is available on a CD–ROM accompanying the printed part of this publication.

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Includes a CD–ROM containing the full document (282 pp.).

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We would like to thank our many colleagues who kindly provided their papers, articles and technical reports for the reviews. The editors would also like to thank Maria Giannini for proofreading the document, Marianne Guyonnet for supervising its publication, and the contributors and participants for their reviews and valuable inputs at the workshop. The document layout specialist was Koen Ivens.

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Abbreviations and acronyms

ADZ	Aquaculture Development Zone
ALSC	Aquaculture Livelihoods Service Center
APP	average physical product
AQCESS	Aquaculture and Coastal Economic and Social Sustainability (EU-funded research project)
ASEAN	Association of Southeast Asian Nations
ASFA	Aquatic Sciences and Fisheries Abstracts
ASSETS	Assessment of Estuarine Trophic Status
AZA	Allocated Zones for Aquaculture
AZE	Allowable Zone of Effects
BIOFAQs	BioFiltration and Aquaculture: an Evaluation of Substrate Deployment Performance with Mariculture Developments (EU-funded research project)
BMP	best management practice
BOD	biological oxygen demand
BP	biosafety protocol
BQE	biological quality element
CBD	Convention on Biological Diversity
CC	carrying capacity
CCRF	Code of Conduct for Responsible Fisheries
CEAA	Canadian Environmental Assessment Act
CFP	Common Fisheries Policy
CITES	Convention on International Trade in Endangered Species of Wild Fauna and Flora
CNPq	Brazilian National Research Council
COC	code of conduct
COPAS	Centro de Investigación Oceanográfica en el Pacífico Sur-Oriental
CRIS	British Columbia Coastal Resource Information System
CZM	coastal zone management
DEAT	Department of Environmental Affairs and Tourism (the Republic of South Africa)
DFID	Department for International Development (United Kingdom of Great Britain and Northern Ireland)
DFO	Department of Fisheries and Oceans (Canada)
DO	dissolved oxygen
DPSIR	Driver-Pressure-State-Impact-Response
DTZ	Dibah Triangle Zone (the Arab Republic of Egypt)
E2K	EcoWin2000
EAA	ecosystem approach to aquaculture
ECASA	Ecosystem Approach for Sustainable Aquaculture (EU FP6 project)
EEZ	exclusive economic zone
EIA	environmental impact assessment
EMP	environmental monitoring programme
EPA	Environmental Protection Agency
EQS	environmental quality standards
EU	European Union
FAO	Food and Agriculture Organization of the United Nations

FCR	food conversion rate
GAFRD	General Authority for Fish Resources Development (the Arab Republic of Egypt)
GAP	good aquaculture practice
GDP	gross domestic product
GEcS	Good Ecological Status
GEnS	Good Environmental Status
GFCM	General Fisheries Commission for the Mediterranean
GHG	greenhouse gas
GIS	geographic information system
GISFish	Global Gateway to Geographical Information Systems, remote sensing and mapping for fisheries and aquaculture
HAB	harmful algal bloom
HACCP	Hazard Analysis and Critical Control Point (system)
HELCOM	Helsinki Commission: Baltic Marine Environment Protection Commission
HR	human resources
IAAS	integrated agriculture–aquaculture systems
IBSFC	International Baltic Sea Fishery Convention
ICES	International Council for the Exploration of the Sea
ICZM	integrated coastal zone management
IFAS	integrated fisheries–aquaculture systems
IMAP	integrated management of aquaculture plans
IMTA	integrated multitrophic aquaculture
IPAS	integrated peri-urban aquaculture system
ISEX	inland sea of the xth region (the Republic of Chile)
IUCN	International Union for Conservation of Nature
KZN	KwaZulu-Natal Province of the Republic of South Africa
LCA	life cycle analysis
LDCS	least-developed countries
LGU	local government unit
LIFDCs	low-income food-deficit countries
LRDW	Land and Resource Data Warehouse (British Columbia)
MedVeg	Effects of Nutrient Release from Mediterranean Fish Farms on Benthic Vegetation in Coastal Ecosystems (EU-funded project)
MERAMED	Development of Monitoring Guidelines and Modelling Tools for Environmental Effects from Mediterranean Aquaculture (EU-funded project)
MMT	million metric tonnes
MOLO	MOm–LOkalisering (Norwegian)
MOM	Modelling-Ongrowing fish farms-Monitoring (model)
MOU	memorandum of understanding
MPA	Ministério da Pesca e Aqüicultura (the Federative Republic of Brazil)
MPA	marine protected area
MPEDA	Marine Products Export Development Authority (the Republic of India)
MPP	marginal physical product
MSFD	Marine Strategy Framework Directive
MTA	multitrophic aquaculture
MTB	maximum permitted biomass
NACA	Network of Aquaculture Centres in Asia-Pacific
NAFO	Northwest Atlantic Fisheries Organization
NASCO	North Atlantic Salmon Conservation Organization
NEAFC	North East Atlantic Fisheries Commission
NELHA	Natural Energy Laboratory of Hawaii Authority

NGO	non-governmental organization
NIFES	National Institute of Nutrition and Seafood Research (the Kingdom of Norway)
NIMBY	not in my backyard
NIMTO	not in my term in office
NPDES	National Pollutant Discharge Elimination System
NWPA	Navigable Waters Protection Act (Canada)
OM	organic matter
OSPAR	Oslo-Paris Convention
PLDM	Local Plans for Mariculture Development (the Federative Republic of Brazil)
PPP	polluter pays principle
PRA	participative rural appraisal
QD	quality descriptors
QQT	quality, quantity and time
RAMA	Aquaculture Environmental Regulation (the Republic of Chile)
REPLA	Aquatic Pest Regulation (the Republic of Chile)
RESA	Aquaculture Sanitary Regulation (the Republic of Chile)
ROV	remotely operated vehicle
RTD	Research and Technology Development
SAMI	Synthesis of Aquaculture and Marine Ecosystems Interactions
SCI	Shellfish Capability Index
SDSS	spatial decision support system
SEA	strategic environmental assessment
SEAFDEC	Southeast Asian Fisheries Development Center
SEPA	Scottish Environmental Protection Agency
SHoCMed	Siting and Holding Capacity in the Mediterranean
SME	small and medium enterprises
SMME	small, medium and microenterprises
SPEAR	Sustainable Options for People, Catchment and Aquatic Resources
SPF	specific pathogen free (shrimp)
SPICOSA	Science and Policy Integration for Coastal System Assessment
SSA	Sub-Saharan Africa
TEK	traditional ecological knowledge
TPP	total physical product
UNCED	United Nations Conference on Environment and Development
USACE	United States Army Corps of Engineers
WFD	Water Framework Directives
WGSC	Working Group on Site Selection and Carrying Capacity
WHO	World Health Organization
WWF	World Wildlife Fund for Nature

Genesis of the workshop

BACKGROUND

Aquaculture is a food production subsector receiving considerable attention for its ability to contribute to filling the growing fish supply gap, which is estimated to be of the order of 40 million tonnes by 2008 rising to 82 million tonnes in 2050 (FAO, 2010a). Aquaculture, however, cannot be practised everywhere; it requires a unique set of natural, social and economic resources. These resources must be wisely used if the development of the subsector is to be sustainable. Around the globe, the availability of areas that are suitable for aquaculture is becoming a major problem for the development and expansion of the sector. The need for sites with appropriate environmental characteristics and good water quality, the social aspects of interactions with other human activities, or conflicts over the use and appropriation of resources inland and along coastal zones are constraints to be considered in the monitoring of existing aquaculture facilities and in the decisions to set up new facilities. Site selection and carrying capacity are among the most important issues for the success of aquaculture, and they need to be carried out in accordance with sustainability, resilience and best practice guidelines.

Although technical guidelines for the FAO Code of Conduct for Responsible Fisheries and the ecosystem approach to aquaculture (EAA) are both available from FAO as reference documents (FAO, 1995; FAO, 2010b), these may require specific consideration for use in different countries and regions, and more explicit guidelines will need to be developed for aquaculture site selection and carrying capacity estimates in inland and coastal aquaculture (Aguilar-Manjarrez, Kapetsky and Soto, 2010).

With the above considerations in mind, the Aquaculture Branch at FAO asked the Sustainable Aquaculture Group at the Institute of Aquaculture, University of Stirling, the United Kingdom of Great Britain and Northern Ireland, to organize a workshop and global review on "Guidelines for Aquaculture Site Selection and Carrying Capacity for Inland and Coastal Aquaculture".

OBJECTIVES

- To prepare global and regional reviews on site selection and carrying capacity encompassing inland aquaculture and coastal aquaculture; to be presented and discussed at the workshop.
- To prepare draft guidelines, including summaries of the key findings and recommendations, for aquaculture site selection and carrying capacity within an ecosystem perspective based on the reviews and the workshop discussions.

IMPLEMENTATION AND PARTICIPATON

The workshop took place from 6–8 December 2010 at the Stirling Management Centre in the University of Stirling, the United Kingdom of Great Britain and Northern Ireland (www.aqua.stir.ac.uk/GISAP/FAO_workshop). The workshop was attended by 20 internationally recognized experts, including two staff members of FAO, and covered different core topics and represented different regions of the world. This was supplemented by written input by the experts for the reviews on "Environmental Impact, Site Selection and Carrying Capacity Estimation for Small-scale Aquaculture in Asia" and on "Guidelines for Aquaculture Site Selection and Carrying Capacity for Inland and Coastal Aquaculture in Mid- and Northern Europe", who were unable to attend the workshop. 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 development and findings

Following a welcome to participants and a general introduction to the agenda and format of the event, the workshop consisted of plenary presentations and brainstorming sessions on a wide range of topics (see Agenda, Annex 1). The scene was set for the workshop through three introductory reviews presentations.

Trevor Telfer summarized the key concepts of the first global review entitled "Carrying Capacities and Site Selection within the Ecosystem Approach to Aquaculture", and highlighted the baseline considerations and also some issues to be resolved for implementation in the aquatic environment. These were discussed in relation to the EAA (FAO, 2010b) and methods of its application in terms of scale, legislation and policy, and implementation. Examples were given from Ireland, the People's Republic of China, the Socialist Republic of Viet Nam and the United Kingdom of Great Britain and Northern Ireland. The importance of decision support systems and incorporation of dynamic and spatial models for their implementation for the different concepts of carrying capacity was highlighted. Based upon this, and throughout the workshop, much attention was given to establishing comprehensive and robust definitions of carrying capacity and its relationship with site selection, with the discussions focusing on the four "pillars" defined by McKindsey *et al.* (2006): physical, production, ecological and social.

Doris Soto presented an overview of the "Ecosystem Approach to Aquaculture and Its Relation to Site Selection and Carrying Capacity", which helped place all the following presentations and discussions in the context of EAA implementation. The three key principles of the EAA, agreed during an FAO Expert Workshop in 2007 (Soto, Aguilar-Manjarrez and Hishamunda, 2008; FAO, 2010b), are:

- Principle 1: Aquaculture development and management should take account of the full range of ecosystem functions and services, and should not threaten the sustained delivery of these to society.
- Principle 2: Aquaculture should improve human well-being and equity for all relevant stakeholders.
- Principle 3: Aquaculture should be developed in the context of other sectors, policies and goals.

José Aguilar-Manjarrez gave an overview of "Spatial Modelling for the Ecosystem Approach to Aquaculture and Its Relation to Site Selection and Carrying Capacity". He noted that spatial tools can support decision-making and modelling within and among all boundaries associated with aquaculture development and management, although it is difficult to prescribe the models to use for site selection and zoning (e.g. hydrodynamic models) because the choice of model depends entirely on the specific issue, study area, scale and research objectives. An ideal scenario for site selection and zoning is one in which a suite of models is developed and computed. It is also important to remember that the better the background data, the more trustworthy the output of the modelling will be.

After the introductory reviews, six additional global review presentations and associated discussion sessions followed, which focused on wide-ranging environmental, socio-economic, legal, spatial and hydrodynamic aspects of site selection and carrying capacity.

João Gomes Ferreira outlined the "Key Drivers and Issues Surrounding Carrying Capacity and Site Selection, with Emphasis on Environmental Components". He noted that virtual technologies of all kinds have a pivotal role in addressing carrying capacity and site selection, although such models do need to be more production oriented. The connectivity between environment and socio-economic aspects also requires further investigation and integration, and there is a need to ensure that production in developing countries should not translate into negative environmental externalities.

Barry Costa-Pierce discussed "Carrying Capacity Tools for Use in the Implementation of an Ecosystems Approach to Aquaculture", with emphasis on the framework for defining the four different types of carrying capacities for shellfish and cage finfish. He outlined new examples of potential decision-making tools for the spatial planning and the ecosystem-based management of aquaculture. He also commented that the ability to estimate different types of carrying capacities is a valuable tool for decision-makers and the public when assessing the impact of development and expansion of aquaculture operations, and can be of use to help develop more sophisticated spatial plans and multiple uses of aquatic space that include aquaculture. The development of more refined and inclusive carrying capacity frameworks and models will help to organize the many available indicators and metrics and allow improved tracking of communications about, and sectoral progress towards, an EAA.

David Little described the "Socio-economic Factors affecting Aquaculture Site Selection and Carrying Capacity". He noted that the location of aquaculture activities has historically been based on a combination on local demand and agro-ecology, with global demand and deteriorating capture fishery stocks having an increasing influence. External interventions to stimulate interest in aquaculture in developing countries have often been driven by geographical and environmental considerations with little regard for other key criteria for successful aquaculture, often resulting in limited development and sustainability. Aquaculture has the potential to cause significant social and economic impacts through the use of chemicals, wastes expelled and stock migration, affecting a range of stakeholders. Similarly, employment along the value chains can bring benefits to people who are not directly involved in farming. He considered that the focus in development programmes should be placed on identifying and responding to local factors rather than allowing top-down, external factors to dominate. Community stakeholder engagement needs to be strengthened, with more rigorous application of cost–benefit analysis and a broad understanding of the social and ecosystem services that are part of aquaculture.

Jorge Bermúdez discussed the "Legal and Policy Components of the Application of the Ecosystem Approach to Aquaculture to Site Selection and Carrying Capacity". He noted that planning decisions should be proactive rather than reactive, recognizing that most major aquaculture concerns have regional or cumulative impacts. Analysis of the legal framework has three major conclusions. First, that from an environmental perspective, carrying capacity allows identification and categorization of appropriate sites. It is important to overcome the site-by-site regulation process. Decisions on site selection are made on an individual basis in response to applications for tenure. This mechanism ignores the fact that many of the major concerns involve regional or cumulative impacts. Second, a range of factors must be considered in order to improve human well-being and equity, and aquaculture carrying capacity is an important aspect of them, although regulators may be unsure of what impacts aquaculture will cause. Third, the objective of the carrying capacity process is to provide appropriate knowledge to the administrative authorities, which may have differing levels of authority. From the site selection perspective, acceptability of aquaculture is linked to stakeholder participation, and sophisticated policy-making is required in order to promote industrial activity and to legitimize the process.

James McDaid Kapetsky described the review entitled "From Estimating Global Potential for Aquaculture to Selecting Farm Sites: Perspectives on Spatial Approaches and Trends". He considered that the spatial domain of site selection and carrying capacity extends from global to local, and suggested that estimating potential (capability for aquaculture development) and zoning (partitioning space for aquaculture) should be added to site selection and carrying capacity. He noted the trend for "all-in-one" applications that include multiple objects (species at different trophic levels and varied culture systems) and multiple functions (site selection, carrying capacity, monitoring for management, including legal aspects), taking into account ecosystem level spatial boundaries, involving active participation or scrutiny by the public, and producing outputs that are highly relevant to managers and aquaculture practitioners. The temporal and spatial scale of such applications needs to be extended and implemented early in aquaculture development planning in a precautionary way and at the national level even where there is less certainty in the results. The main bottlenecks to implementing broad scale spatial analyses are lack of data of appropriate resolution and variety of input data for models, as well as the apparent problem of disseminating the techniques and building the capacities to utilize them.

Arnoldo Valle-Levinson outlined "Some Basic Hydrodynamic Concepts to Be Considered for Coastal Aquaculture". Sustainable coastal aquaculture requires a combination of field measurements and numerical model implementation, calibration and validation. Basic forcing agents that need to be considered in a study are freshwater discharge (and its seasonal variability), atmospheric forcing (with its synoptic and seasonal variability), tidal forcing (with semidiurnal, fortnightly and seasonal variability), bathymetric effects, and earth's rotation effects. These forcing agents determine temporal and spatial variations of relevant parameters, such as hydrography, dissolved oxygen and nutrients. A three-stage process was proposed based on simple criteria for the location of a fish cage, or fish cage cluster, as well as a simple criterion based on the tidal excursion at a given aquaculture site for optimal individual fish cage or fish cage cluster separation. This allows determination of "ellipses of influence" for a given cluster or cage, which indicates the potential area in the body of water that may be influenced by suspended and dissolved materials associated with aquaculture activities.

The workshop devoted further sessions to the presentation and associated discussions of ten regional reviews with a specific geographic focus, covering the major continents and ranging from intensive to extensive implementations of carrying capacity and current regulation in different countries.

Ioannis Karakassis reviewed "Environmental Interactions and Initiatives on Site Selection and Carrying Capacity Estimation for Fish Farming in the Mediterranean". He outlined the extensive consultative processes for the area, and the role that FAO and the General Fisheries Commission for the Mediterranean have taken to assist cooperation for the development of aquaculture and to enhance the dialogue among Mediterranean States and stakeholders regarding three main issues, i.e. site selection and carrying capacity, sustainability indicators and marketing of aquaculture products.

Anne-Katrine Lundebye Haldorsen considered "Aquaculture Site Selection and Carrying Capacity for Inland and Coastal Aquaculture in Northern Europe", giving specific emphasis to the integration of aquaculture approaches in the Kingdom of Norway, currently the largest aquaculture producing country in Europe, with regulation and governance. She noted that the Modelling-Ongrowing fish farms-Monitoring (MOM) model in use in Scandinavia is primarily meant to estimate the holding capacity of new sites for fish farming, but that it may also be used to assess the environmental consequences of changes in production on farms already in operation. It was recommended that, in order to expand aquaculture in European coastal waterbodies, farming techniques should be developed to reduce environmental

impacts. In the Kingdom of Norway, this involves combating the problem of salmon lice and reducing the number of escapees from salmon farms. An increased production from inland aquaculture is most likely achievable by intensification at existing sites and further development of recirculation aquaculture systems to reduce water and energy consumption and to reduce nutrient emission to the environment.

Sherif Sadek reviewed "Aquaculture Site Selection and Carrying Capacity Estimates for Inland and Coastal Aquaculture in the Arab Republic of Egypt". He described how carrying capacity management status can assist and protect the durability of this important industry. The effect of rapid expansion of the industry on environmental sustainability was outlined along with such issues as environmental pressure and pollution caused by agricultural and industrial development, all of which affect aquaculture carrying capacity. He emphasized the need for spatial management through appropriate zoning to control water quality and to minimize effects on communities.

Ruby Asmah summarized "Aquaculture Site Selection and Carrying Capacity Estimates for Inland and Coastal Aquaculture in West Africa", focusing on the state of aquaculture development in the West African region, current criteria and approaches for site selection within the region, considering current legislation, regulations and actual compliance, and finally describing the main carrying capacity and site selection issues, gaps in information and local needs. Current environmental law was summarized as was the use of models and decision support tools in the subregion, noting that current site selection procedures are based on individual site assessment, which could be lengthy and subjective. Although the environmental and social impacts of a single farm might seem unimportant, more attention must be paid to the potentially cumulative ecosystem effects of groups of farms at particular sites. She proposed that the first step needed to bring aquaculture site selection in the subregion in line with the EAA principles is to create awareness of these principles, train stakeholders and relevant regulatory bodies on the requirements of these principles, and equip relevant institutions with the necessary tools to be able to implement them.

Martin De Wit considered "Aquaculture in Southern Africa with Special Reference to Site Selection and Carrying Capacity Issues". He identified a series of obstacles to sustainable development of aquaculture in the region, including lack of start-up capital, that planned site selection is expensive and time consuming, the need to engage with the EAA, the impacts of introduced trout on endemic species, the impact of farm effluents on carrying capacity, the cost of accurate risk assessments, and that the culture of indigenous species may be used as a front for the sale of wild-poached products. All of these complex environmental and societal influences have a strong effect on estimates of carrying capacity and site selection.

Changbo Zhu described "Aquaculture Site Selection and Carrying Capacity Management in the People's Republic of China". He emphasized the significant impact that fisheries and aquaculture have had on Chinese living standards and food security. As the largest aquatic food producer in the world, the People's Republic of China has already exploited most of its suitable waterbodies and land. Consequently, factors relevant to aquaculture site selection in the People's Republic of China include functional zoning schemes for local land and water areas, water and other environmental quality requirements, influence on the local environment, and the influence on community welfare. Local issues affecting sustainable development of aquaculture include farming at the limits of carrying capacity, environmental pressure and deterioration caused by industrialization, rapid expansion of inland freshwater shrimp farming, and the predicament of aquaculture-related law enforcement. The continuous increase in fed aquaculture may lead to a reduction in net food production and increasing environmental pressures. The current bottlenecks limiting reasonable aquaculture site selection and carrying capacity management in the

People's Republic of China relate to water area zoning scheme enforcement and the lack of effective monitoring and legislation on aquaculture effluent discharge. Optimization of sustainable aquaculture in the People's Republic of China depends upon the revision of these factors as well as the revision of product price to include the environmental cost.

Patrick White provided a review of "Environmental Impact, Site Selection and Carrying Capacity Estimation for Small-scale Aquaculture in Asia". He highlighted the continuing importance of aquaculture in Asia to provide livelihoods, food security and export earning power, but at the same time highlighted the problems with the environmental impact from the large numbers of small-scale producers and the difficulties in planning and management of further development. He identified a number of difficulties for the sector and emphasized a need for greatly improved sectoral planning, to include strategic aspects, zoning, and use of clustering of activities in aquaculture parks. The use of appropriate modelling tools was noted, mainly aimed at improved management systems, clusters, and wider producer networks of clusters, for which national aquaculture agencies should be encouraged to provide extension and training support.

Stephen Cross gave an overview of "Carrying Capacity and Site Selection Tools for Use in the Implementation of an Ecosystem-based Approach to Aquaculture in Canada: a Case Study". He discussed current practice and carrying capacity issues in coastal British Columbia, Canada, illustrating how this jurisdiction currently manages aquaculture site selection and operations, and how ongoing changes to its overarching policy and regulatory processes relate to the development of an EAA. Environmentally, carrying capacity issues are addressed using a combination of geographic information systems (GIS)-based resource modelling and spatial separation guidelines, waste dispersion models such as DEPOMOD to run simulations of organic waste dispersion/accumulation, and performance-based monitoring using physical-chemical surrogates of biological response to ecosystem stress. The environmental tools for carrying capacity and site selection are not applied equally to all aquaculture culture systems, and deficiencies in the approach are recognized as significant gaps to forming a comprehensive and defensive EAA. Socially, British Columbia aquaculture competes with a variety of coastal activities, and new initiatives to assess social-ecological performance, in the form of a sustainability report, have been introduced, holding the promise of communicating the positive attributes of an EAA.

Philip Scott reviewed "Regional and National Factors Relevant to Site Selection for Aquaculture in the Federative Republic of Brazil", and illustrated how aquaculture and fisheries production had grown over the last decade to 1.24 million tonnes in 2009. Aquaculture, specifically, grew by 49 percent between 2003 and 2009, although this growth has taken place in spite of many drawbacks and has been strongly based on private sector initiatives. Initial difficulties faced by aquaculturists in the Federative Republic of Brazil included the lack of specific environmental legislation, existence of costly licence fees, and public prices beyond the means of small producers. In contrast to terrestrial agricultural activities, there have also been difficulties in handling the complexity of information necessary for the licensing process, a lengthy consultation process, and generally poor access to "aqua" credit. Consequently, there has been little if any stimulus for investment in aquaculture, much less good production practices, this being especially the case for small farmers. Nonetheless, carrying capacity models have recently been used for freshwater aquaculture, especially in large reservoirs whose primary function is hydroelectric generation. The trade-off between "environmental services" of the many relatively recently developed artificial ecosystems in the context of an EEA is difficult. GIS has been used to support several marine aquaculture projects.

Alejandro Clément reviewed the "Ecosystem Approach and Interactions of Aquaculture Activities in Southern Chile". He illustrated the interactions among different aquaculture activities in the coastal zone and inland sea in southern Chile. Particular emphasis was given to negative ecological events observed during the last decade. He considered the need for robust marine surveys and models for environmental prediction and decision support to site selection and zoning, noting that only when these were available and reliable would it be possible to estimate the relative amounts and inputs of "new production" from aquaculture with those natural fluxes in the sea.

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Workshop recommendations and the potential role of FAO

RECOMMENDATIONS

Presentations at the workshop demonstrated how different categories of carrying capacity may be used either in isolation or in combination to address site selection and sustainability of aquaculture.

Participants agreed that estimation of carrying capacity for aquaculture development almost always requires a multifaceted approach, which is covered by at least four categories – physical, production, ecological and social.

Physical carrying capacity is best considered as a primary and broader site selection criterion, while the remaining categories determine the real and effective carrying capacity, with the possible extension to include economic carrying capacity.

It was also agreed that participatory consultation with a full stakeholder range was essential and that such consultation should include consideration of acceptable change.

It was agreed that carrying capacity estimates should be iterative and revisited beyond any initial development, to allow for re-evaluation of sites periodically and to apply corrective measures when needed.

It was recommended that FAO should promote the use of these components in addressing carrying capacity within the framework of the EAA.

There should be a greater awareness of the range of modelling tools to assist carrying capacity estimation and support decision, as well as training activities in their use.

It was also noted how GIS and associated spatial tools can contribute to holistic modelling of carrying capacity to support and facilitate the implementation of the EAA. However, an enabling environment is crucial to adopt the use of spatial tools to support the EAA, and FAO can contribute by promoting their use and supporting more extensive training for end users.

There is a continuing need to gauge capacities (human resources, infrastructure, finances) at the national and/or regional level to implement the use of appropriate modelling and spatial tools in support of the EAA so that capacity-building initiatives can be matched to existing capabilities.

It was agreed that training needs should be met using appropriate modes of delivery to include both face-to-face training and online workshops and seminars.

Participants agreed that some guidance on how to approach estimates of carrying capacity and site selection are needed. Implementation of a more comprehensive and holistic approach to carrying capacity estimation and site selection needs to be encouraged by increasing awareness of benefits.

As a practical first step, development of a set of guidelines was recommended to illustrate the approach and uses of modelling to address carrying capacity, particularly in relation to the EAA, and using a selection of case studies from different regions, environments, species and culture systems.

THE POTENTIAL ROLE OF FAO AND THE WAY FORWARD

FAO should continue to assist the aquaculture sector to grow in a sustainable manner, taking into account food security on the one hand while robustly addressing issues of site selection and carrying capacity to ensure sustainability.

Under the umbrella of the EAA, which has already been effectively promoted by FAO, the organization should strongly promulgate the concepts of carrying capacity

for proper siting of aquaculture developments as proposed by this workshop.

FAO is in a position to provide strong worldwide leadership for more holistic aquaculture project development, which must comprise the full range of components identified under the EAA and include the various facets of carrying capacity as defined in these proceedings.

FAO could consider how to embed best practice across the sector by promoting and providing the training in the concepts and use of support tools that will be essential to extending the EAA and carrying capacity concepts worldwide.

Key outputs from this workshop are these proceedings, which includes a synthesis of the current workshop experts' position on "Carrying Capacities and Site Selection within the Ecosystem Approach to Aquaculture".This document will then form the basis for the guidelines on implementation of carrying capacity and site selection for inland and coastal aquaculture, within the EAA, to be published by FAO.

Subsequently, the wide dissemination of the present report and the accompanying guidelines will be key to effective and more widespread adoption by policy-makers and stakeholders worldwide.

Annex 1 – Agenda

Expert Workshop on Site Selection and Carrying Capacities for Inland and Coastal Aquaculture
Institute of Aquaculture, University of Stirling, the United Kingdom of Great Britain and Northern Ireland
5–8 December 2010

DATE	TIME	ACTIVITY
5–12–10		Arrival of participants
6–12–10	08:30	Coffee
	09:00	Welcome and introduction to the workshop – Lindsay G. Ross
	09:30	Carrying capacities and site selection within the ecosystem approach to aquaculture – a global review for a scene-setting discussion – Trevor C. Telfer
	10:00	Ecosystem approach to aquaculture and its relation to site selection and carrying capacity – Doris Soto
	10:30	Spatial modelling for the ecosystem approach to aquaculture and its relation to site selection and carrying capacity – José Aguilar-Manjarrez
	11:00	Coffee
	11:30	Discussion: Agreeing on a basis for carrying capacity in the aquaculture context
	12:00	Key drivers and issues surrounding carrying capacity and site selection, with emphasis on environmental components – João Gomes Ferreira Laudemira Ramos and Barry A. Costa-Pierce
	12:30	Carrying capacity tools for use in the implementation of an ecosystems approach to aquaculture – Carrie J. Byron and Barry A. Costa-Pierce
	13:00	Lunch
	14:00	Socio-economic factors affecting aquaculture site selection and carrying capacity – David Little
	14:30	Legal and policy components of the application of the ecosystem approach to aquaculture to site selection and carrying capacity – Jorge Bermúdez
	15:00	From estimating global potential for aquaculture to selecting farm sites: perspectives on spatial approaches and trends – James McDaid Kapetsky and José Aguilar-Manjarrez
	15:30	Coffee
	16:00	Some basic hydrodynamic concepts to be considered for coastal aquaculture – Arnoldo Valle-Levinson
	16:30	Discussion and round-up of the day's presentations

DATE	TIME	ACTIVITY
7–12–10	08:30	Coffee
	09:00	Environmental interactions and initiatives on site selection and carrying capacity estimation for fish farming in the Mediterranean – Ioannis Karakassis
	09:30	Aquaculture site selection and carrying capacity for inland and coastal aquaculture in Northern Europe – Anne-Katrine Lundebye Haldorsen
	10:00	Aquaculture site selection and carrying capacity estimates for inland and coastal aquaculture in the Arab Republic of Egypt – Sherif Sadek
	10:30	Coffee
	11:00	Aquaculture site selection and carrying capacity estimates for inland and coastal aquaculture in West Africa – Ruby Asmah
	11:30	Aquaculture in Southern Africa with special reference to site selection and carrying capacity issues – Martin De Wit
	12:00	Aquaculture site selection and carrying capacity management in the People's Republic of China – Changbo Zhu and Shuanglin Dong
	12:30	Environmental impact, site selection and carrying capacity estimation for small-scale aquaculture in Asia – Patrick G. White, Michael Phillips and Malcolm Beveridge
	13:00	Lunch
	14:00	Carrying capacity and site selection tools for use in the implementation of an ecosystem-based approach to aquaculture in Canada: a case study – Stephen F. Cross
	14:30	Regional and national factors relevant to site selection for aquaculture in the Federative Republic of Brazil – Philip C. Scott
	15:00	Ecosystem approach and interactions of aquaculture activities in southern Chile – Alejandro Clément
	15:30	Coffee
	16:00	Working group discussions on: inputs, process and implementation
	19:30	Dinner – with guest Professor Brian Austin (Director of the Institute of Aquaculture) and Professor Ian Simpson (Deputy Principal Research and Head of the School of Natural Science)
8–12–10	08:30	Coffee
	09:00	Plenary discussion of definitions of carrying capacity and interactions with site selection
	11:00	Coffee
	11:30	Presentations of deliberations of working groups
	13:00	Lunch
	14:00	Presentation of draft outline for proceedings and guidelines and concluding discussions
	15:30	Closure of the workshop

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Global Reviews

Carrying capacities and site selection within the ecosystem approach to aquaculture

Ross, L.G., Telfer, T.C., Falconer, L., Soto, D., Aguilar-Manjarrez, J., Asmah, R., Bermúdez, J., Beveridge, M.C.M., Byron, C. J., Clément, A., Corner, R., Costa-Pierce, B.A., Cross, S., De Wit, M., Dong, S., Ferreira, J.G., Kapetsky, J.M., Karakassis, I., Leschen, W., Little, D., Lundebye, A.-K., Murray, F.J., Phillips, M., Ramos, L., Sadek, S., Scott, P.C., Valle-levinson, A., Waley, D., White, P.G. & Zhu, C. 2013. Carrying capacities and site selection within the ecosystem approach to aquaculture. *In* L.G. Ross, T.C. Telfer, L. Falconer, D. Soto & J. Aguilar-Manjarrez, eds. *Site selection and carrying capacities for inland and coastal aquaculture,* pp. 19–46. FAO/Institute of Aquaculture, University of Stirling, Expert Workshop, 6–8 December 2010. Stirling, the United Kingdom of Great Britain and Northern Ireland. FAO Fisheries and Aquaculture Proceedings No. 21. Rome, FAO. 282 pp.

Abstract

The growth in world aquaculture required to meet the demands of society will result in ever-increasing pressure upon aquatic and terrestrial resources. There are also potential consequences on the environment and on biodiversity, as well as inevitable societal impacts. There is growing adoption of aspects of the ecosystem approach to aquaculture (EAA), which takes a holistic view of the developments in the sector in an attempt to enable sustainable growth while avoiding negative effects. Carrying capacity is a major component of EAA, but defining what is meant by carrying capacity, how to evaluate it and how to implement standards is not a straightforward matter. This global review summarizes present views on this topic, and considers definitions of the different carrying capacities and methods and models for their evaluation. It also identifies some outstanding questions and bottlenecks. Proposals are made for a way forward that may result in flexible guidelines for implementing well-planned site selection and carrying capacity estimations within the EAA.

Introduction

Worldwide, aquaculture will need to increase production significantly during the next few decades to ensure sufficient animal protein supply to the increasing human population (Duarte *et al*., 2009). Though the majority of aquaculture throughout the world is undertaken in freshwater systems, use of coastal and shelf ecosystems for aquaculture will increase substantially, putting even greater environmental pressures on their ecosystem goods and services.

The location of aquaculture activities has historically been based on a combination of local demand and agro-ecology, with global demand and deteriorating capture fishery stocks having an increasing influence (Little *et al*., 2012). External interventions aimed at stimulating aquaculture growth have often been driven by short-term objectives and geo-political boundaries without paying enough attention to other key criteria for successful aquaculture, often resulting in limited development and sustainability. Established and developing aquaculture sectors have sometimes "clustered" around

important resources or services, to greater effect, taking into account a wide range of factors including the environment, proximity to markets and transportation links. These drivers have been most relevant in aquaculture development, especially in Asia-Pacific where the sector originated and the region with the largest production. However, continuous expansion is not always possible, and in many places the siting of farms is considered suboptimal, limiting production.

Any growth in aquaculture production will involve an expansion of cultivated areas, a higher density of aquaculture installations and the increased use of feeds, fertilizer and chemical inputs, as well as increased land and water use. Because aquaculture is a resource-based activity, which competes for economic, social, physical and ecological resources with other industries, its development could have negative impacts on industries such as fisheries, agriculture and tourism. In addition, use of environmental goods and services leads to impacts that can have both social and economic implications (FAO, 2008). As a result, it is vital that the carrying capacity of these systems is considered integral to the development and site selection process for aquaculture activities, and is inherent in adoption of good practices and sound environmental regulation to ensure the sustainability of aquaculture-based food production.

Other frameworks and institutions such as the European Union Water Framework Directive, the Marine Strategy Framework Directive, Canada's Oceans Act, and the United States of America National Policy for the Stewardship of the Ocean, Coasts and Great Lakes all call for spatial planning for human activities, such as aquaculture, to be carried out in a more sustainable fashion, including the essential components of: (i) knowledge-based approaches for decision-making; and (ii) ecosystem-based approaches for integrated management.

The objective of this paper is to review critically the concepts of carrying capacity and aquaculture spatial location within the framework of EAA development and to suggest a strategy for their implementation to ensure greater sustainability for future inland and coastal aquaculture developments throughout the world.

Concepts of carrying capacity

Carrying capacity is an important concept for ecosystem-based management, which helps set the upper limits of aquaculture production given the environmental limits and social acceptability of aquaculture, thus avoiding "unacceptable change" to both the natural ecosystem and the social functions and structures. In general terms, carrying capacity for any sector can be defined as the level of resource use both by humans or animals that can be sustained over the long term by the natural regenerative power of the environment. This is complementary to assimilative capacity, which is defined as "the ability of an area to maintain a healthy environment and accommodate wastes" (Fernandes *et al.,* 2001), and to environmental capacity, which is defined as "the ability of the environment to accommodate a particular activity or rate of activity without unacceptable impact" (GESAMP, 1986). In addition to the above, Davies and McLeod (2003) defined carrying capacity as "the potential maximum production a species or population can maintain in relation to available food resources". Assessment of carrying capacity is one of the most important tools for technical assessment of not only the environmental sustainability of aquaculture as it is not limited to farm or population sizes issues, but it can also be applied at ecosystem, watershed and global scales. Although these general views of carrying capacity for aquaculture are based solely on production, they have been developed further into a more comprehensive four-category approach based on physical, production, ecological and social carrying capacity (Inglis, Hayden and Ross, 2000; McKindsey *et al*., 2006). Although these accepted definitions were originally described specifically for bivalve aquaculture, they have also been applied to finfish cage culture (Gaĉek and Legović, 2010).

- *Physical carrying capacity* is based on the suitability for development of a given activity, taking into account the physical factors of the environment and the farming system. In its simplest form, it determines development potential in any location, but is not normally designed to evaluate that against regulations or limitations of any kind. In this context, this can also be considered as identification of sites or potential aquaculture zones from which a subsequent more specific site selection can be made for actual development.
- This capacity considers the entire waterbody, or waterbodies, and identifies the total area suitable for aquaculture. Inglis, Hayden and Ross (2000) and McKindsey *et al.* (2006) note that physical carrying capacity does not indicate at what density cultured organisms are stocked or their production biomass. Physical carrying capacity is useful to quantify potential adequate and available areas for aquaculture in the ecosystem, but it offers little information on aquaculture's limits at the waterbody or watershed level within the EAA. In terrestrial aquaculture, it can define the capacity of the area for the construction of ponds or the availability of water supply.
- *Production carrying capacity* estimates the maximum aquaculture production and is typically considered at the farm scale. For the culture of bivalves, this is the stocking density at which harvests are maximized. However, production biomass calculated at production carrying capacity could be restricted to smaller areas within a water basin so that the total production biomass of the water basin does not exceed that of the ecological carrying capacity, for example, fish cage culture in a lake.
- Estimates of this capacity are dependent upon the technology, production system and the investment required, with investment being defined by Gibbs (2009) as an "economic" capacity, being the biomass at a particular location for which investment can be secured.
- *Ecological carrying capacity* is defined as the magnitude of aquaculture production that can be supported without leading to significant changes to ecological processes, services, species, populations or communities in the environment.
- Gibbs (2007) discussed a number of issues pertaining to the definition and calculation of ecological carrying capacity, and highlighted the fact that bivalve aquaculture can have an impact on the system because bivalves are both consumers (of phytoplankton) and producers (by recycling nutrients and detritus) with the concomitant ecosystem impacts of both. In determining ecological carrying capacity, he has urged caution when attributing cause of change (and partitioning impacts) between bivalve culture and other activities in the ecosystem. On the other hand, fish cage culture, for example, uses ecosystem services for the degradation of organic matter and nutrients and provision of oxygen, but a certain level of fish biomass may exceed the system capacity to process nutrients and provide oxygen, thus generating eutrophication.
- *Social carrying capacity* has been defined as the amount of aquaculture that can be developed without adverse social impacts.

Byron *et al.* (2011) have stated that the ultimate goal of determinations of social carrying capacity is to quantify the value of the involvement of stakeholders in a science-based effort to determine the proper limits to aquaculture in their local waters. Ecological degradation or adverse changes to ecosystems attributed to aquaculture may inhibit social uses. According to Byron *et al.* (2011), the point at which alternative social uses become prohibitive due to the level, density or placement of aquaculture farms is the social carrying capacity of aquaculture. Angel and Freeman (2009) refer to social carrying capacity as the concept reflecting the trade-offs among all stakeholders using common property resources and as the most difficult to quantify, but as the most critical from the management perspective. For example, if there is widespread opposition to aquaculture in a particular place, the prospects for its expansion will be limited.

According to Little *et al.* (2012), aquaculture has the potential to exert significant social and economic impacts through upstream and downstream links around the use of water, seed, feed, chemicals, wastes expelled, etc. This incorporates a broad section of people as stakeholders. Similarly, employment along the value chains, both upstream and downstream, brings benefits to many people not directly involved in farming. Such implications can make the setting of boundaries for the estimation of social carrying capacity very challenging.

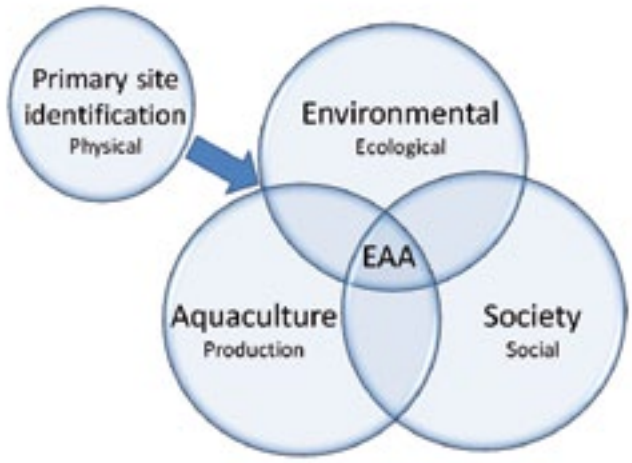
The ecosystem approach to aquaculture as a framework for carrying capacity

In 2006, the FAO Fisheries and Aquaculture Department recognized the need to develop an ecosystem-based management approach to aquaculture to strengthen the implementation of the FAO Code of Conduct for Responsible Fisheries (FAO, 1995). FAO proposed an ecosystem approach to aquaculture (EAA), defined as a *strategy for the integration of aquaculture within the wider ecosystem such that it promotes sustainable development, equity, and resilience of interlinked social-ecological systems* (Soto, Aguilar-Manjarrez and Hishamunda, 2008; FAO, 2010). The strategy is guided by three key principles, namely:

- Principle 1: Aquaculture development and management should take account of the full range of ecosystem functions and services, and should not threaten the sustained delivery of these to society.
- Principle 2: Aquaculture should improve human well-being and equity for all relevant stakeholders.
- Principle 3: Aquaculture should be developed in the context of other sectors, policies and goals.

It is recognized that defining, developing and adapting existing methods to estimate resilience capacity, or the limits to "acceptable environmental change", are essential tasks to moving forward with an EAA. Changes in the regulatory framework have recently led to a more stringent approach to licensing in many countries, e.g. in the European Union, Canada, the Republic of Chile and the United States of America. Nevertheless, only in a few countries (e.g. Ferreira *et al.*, 2008a) has there been a concern with the assessment of carrying capacity at the system scale, i.e. to define and quantify potential *aquaculture zones* as an initial step prior to local-scale licensing of aquaculture operations.

FIGURE 1
Interaction of the different categories of site identification and carrying capacity to arrive at an ecosystem approach to aquaculture. After primary site identification the process can pass on to any or all of the three other areas

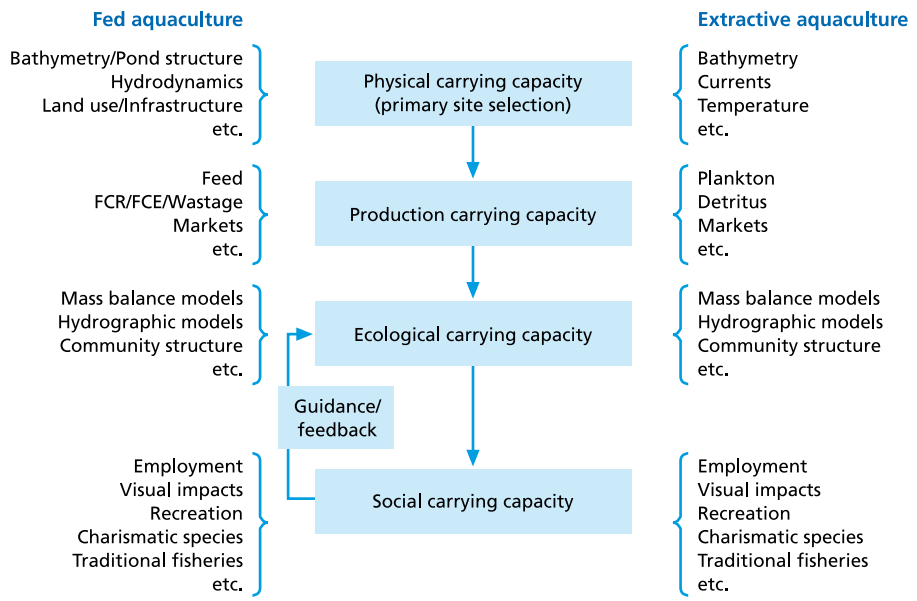


The application of the EAA at different geographical scales requires the harmonization of three objectives that comply with the EAA principles: (i) environmental; (ii) socio-economic; and (iii) governance, including multisectoral planning (FAO, 2010). These three objectives and their relative weights can differ among countries and across world regions, making it challenging to define a single standard for uniform compliance with respect to limits and thresholds.

The four carrying capacity categories as defined by McKindsey *et al.* (2006) can be weighted according to region and aquaculture system. Thus, the three core objectives of EAA can be mapped onto the four categories of carrying capacity, and illustrated as the overlap of these (Figure 1). The social category covers the socio-economic and governance objectives of the EAA as indicated above. The importance (size) of each circle represented will vary regionally or with culture system and will develop through time based on the feedback society provides. However, the need for harmonization of the three EAA objectives for the long-term sustainability of aquaculture must be kept in mind.

McKindsey *et al.* (2006) proposed a hierarchical structure to determine the carrying capacity of a given area, where the first stage would involve determining the physical carrying capacity or suitability of a site based on the natural conditions and needs of the species and culture system, followed by the calculation of the production carrying capacity of the available area using models (Figure 2). Models would also be used in the next stage to estimate the ecological carrying capacity and evaluating the range of potential outcomes for production ranging from no production to maximum production level, as determined in the previous step. The final stage would be to assess the different scenarios based on the outcomes from each of the previous steps and then make a decision on the level of acceptable productivity; this would introduce the social carrying capacity. The first two steps of the process (physical and production carrying capacities) do not depend on social values, whereas both ecological and social carrying capacities do. This requires environmental variables of interest to be defined by society before determining the ecological carrying capacity.

FIGURE 2
Hierarchical structure to determine carrying capacity of a given area. Social carrying capacity feeds back directly to ecological carrying capacity to provide guidance to choose pertinent response variables to measure



Source: modified from McKindsey *et al*. (2006).

Salient characteristics of aquaculture potential, zoning, siting and carrying capacity, including purpose, scope, scales, executing entity, data needs, required resolution and results obtained, are proposed in Table 1 in order to show how these activities relate to one another. This approach is most appropriate when new developments are being considered or when there is little or no prior aquaculture activity in the area. Potential, siting and zoning for aquaculture are all development activities that may

follow a temporal and spatial progression, beginning with estimating potential and ending with site selection. In terms of spatial scale, potential has the broadest reach, zoning is intermediate, and site selection is the narrowest. Carrying capacity has to be considered at all stages of development and management. The temporal progression for the first three activities needs to be repeated as culture systems are developed for new species or are modified for species already under culture. In addition, carrying capacity must also be reassessed when changing economic or infrastructure situations make previously unsuitable locations newly attractive for investment.

TABLE 1
Main characteristics/steps of the process to estimate potential, zoning, siting and carrying capacity for aquaculture

Characteristics	Culture potential	Zoning	Siting	Carrying capacity estimate
Main purpose	Plan strategically for development and eventual management	Regulate development; minimize competing and conflicting uses; reduce risk; maximize complementary uses of land and water	Reduce risk; optimize production	Sustain culture; protect environment/ ecosystem; reduce risk
Spatial scope: administration	Global to national	Subnational	Farm or farm clusters	Farm or farm clusters
EAA scale	Global	Watershed or waterbody	Farm/s	Farm area to watershed or waterbody
Executing entity	Organizations operating globally; national aquaculture departments	National, state/ provincial/ municipal governments with aquaculture responsibilities	Commercial entities	Regulating agencies
Data needs	Basic, relating to technical and economic feasibility, growth and other uses	Basic environmental, social and economic sets	All available data	Data to drive models
Required resolution	Low	Moderate	High	High
Results obtained	Broad, indicative	Directed, moderately detailed	Specific, fully detailed	Moderately to fully detailed

Note: In general, culture potential and zoning involve physical carrying capacity, while the specific siting of a farm will require production, ecological and social capacity estimates, in addition to refinement of physical capacity, to ensure sustainability of the farming system at the specific site.
Source: Modified from Kapetsky and Aguilar-Manjarrez (2012).

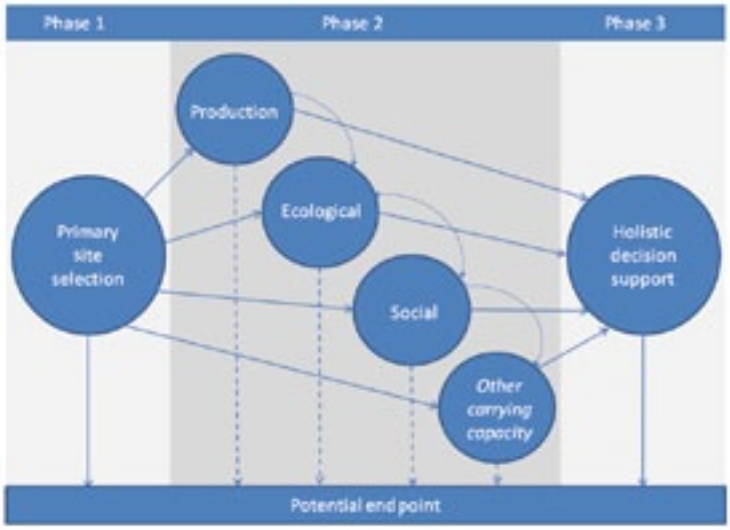
The starting point for deciding how to address the various components of site selection and carrying capacity will depend upon the nature of the problem and the level at which it is being evaluated. Clearly, some recommendations for a standardized methodology would be useful, particularly for people who are confronting this complex issue for the first time. For example, is consideration of all four categories of carrying capacity a necessity, and is it a parallel or sequential process?

Broad, strategic planning decisions may be built upon site selection, which is at first left unrestricted by any existing regulations. This follows the logic that the physical evaluation should form an unbiased site selection baseline that disregards any regulatory or otherwise restrictive aspects of carrying capacity and any other influences, such as

competing land uses. This sequence was also advocated by McKindsey *et al.* (2006). Further site-related considerations at a national or regional level may be the strategic development of sites clustered or agglomerated into aquaculture zones, or aqua parks, as has occurred in many locations worldwide.

Once an area has been identified as suitable for development, much more detailed work may need to be done to address carrying capacity within its full regulatory framework, and this may include complex production, environmental and societal influences. From this baseline, all other categories then act as real estimates of carrying capacity and can be in a manner that either serves to eliminate areas by constraining them, or acts to rank the primary evaluation against established regulatory criteria. The sequence and structure of this approach, and its potential feedback and end-points, are shown in Figure 3. Some components of the process will depend upon a "knowledge base", primarily of biological and environmental variables, while others may be driven more by matters of food security and socio-economic targets. It must be accepted that what may be considered as more objective scientific decision-making may often be overridden by political requirements. A prime example of this is the concessions made to Canada's First Nations for local distinctiveness (Cross, 2012).

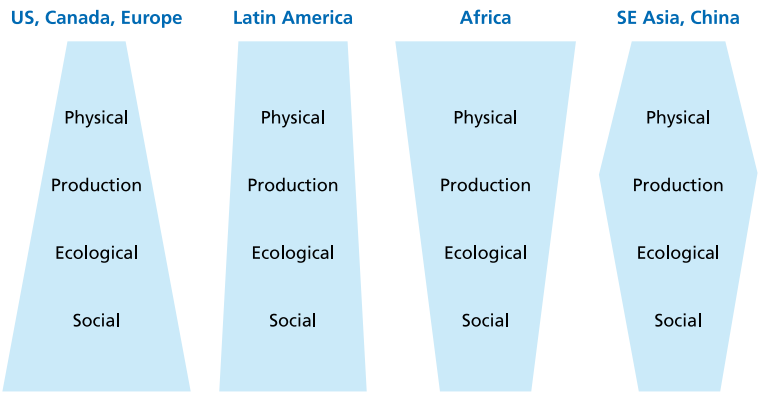
FIGURE 3
Schematic approach to the relationships and possible sequencing of the different carrying capacity categories, showing the range of end-points in the decision process. The order or priority in the second phase can be case specific



Investigation and modelling of any of the individual categories of carrying capacity can be used as a free-standing decision support tool for carrying capacity, and it may be that important decisions may be possible based upon a single component. This may enable early selection or regulatory decisions that reduce or eliminate the necessity for investigation of other capacities. However, in most cases, more than one category of carrying capacity will need to be investigated, and for comprehensive, holistic decision-making, all will be needed. In this case, the priority assigned to a given carrying capacity category will vary with location, depending upon national or regional priorities, as well as environmental, cultural and social issues. There is, thus, probably no obvious, single, preferred sequence of development of these four categories.

In all multi-criteria decision processes, it is frequently the case that some factors are more important than others, perhaps considerably so, and this is well known in spatial analytical modelling. The same principle applies in the case of multi-component carrying capacity estimation, and a logic can be developed whereby the different categories are brought together, taking into account the differing degrees of importance set by national or local priorities and policies. For example, in the "West" there can be considerable social pressure for regulation of all production activities, including aquaculture, while in the "East" there may be greater deregulation and political flexibility aimed at maximizing productivity (Figure 4).

FIGURE 4
An example of differential prioritisations of the four pillars in different world regions. The width of the polygon is an indication of relative importance



Source: Modified from Ferreira *et al*. (2012).

Aquaculture systems and species cultured vary considerably across the world, and can be either feed based or organically extractive in nature. Both of these culture types can occur in open coast marine systems or inland freshwater systems. Site selection is highly dependent on the type of aquaculture system, the location and interactions between the systems, and the surrounding environment (Table 2).

TABLE 2
Examples of the main issues currently considered in site selection, together with what may constitute future components for assessment.

Type	Present	Future
Feed-based aquaculture (e.g. cages, ponds)	Site selection based on maximizing production, waste dispersion (cages), wastewater minimization (ponds)	Integrated model systems, risks, welfare, disease Holistic indicators Life-cycle analysis: inefficiencies and ecolabelling Mechanistic and statistical models Data assimilation models Maximizing production
Shellfish farming	Large areas Harmful algal blooms Focus on production and social carrying capacity	Economic sustainability, ecology and economics Coupled GIS expert systems including xenobiotics harmful algal blooms, etc. Model uncertainties in yield Early warning
Integrated multitrophic aquaculture	Optimize production Reduce negative externalities	Combination with integrated coastal zone management Simulation of species combinations Full economic assessment. Combine GIS, remote sensing and modelling

Source: Modified from Ferreira, Ramos and Costa-Pierce (2012).

Feed-based aquaculture in cages (open water environments) or ponds (inland or fringing environments) is mainly constrained by physical capacity and wastewater reduction criteria. In Southeast Asia and the People's Republic of China, there is greater preoccupation with production and physical capacities, whereas in the European Union and the United States of America legislation ensures greater emphasis on negative externalities.

Extractive aquaculture, because of the nature of its food intake, normally occupies relatively large areas, often including large shorefront leases. The issues that have emerged with respect to carrying capacity have been largely (i) production related, such as the reduced growth and harvest size of the Pacific oyster (*Crassostrea gigas)* in the Marennes-Oléron area of the French Republic in the mid-1990s, which was mainly attributed to overstocking (Raillard and Ménesguen, 1994); or (ii) social concerns in developed nations on the use of waterfront areas (e.g. the geoduck industry in Puget Sound, Cheney *et al.*, 2010), landscape values, etc. The physical carrying capacity for extractive species may be already limited in some parts of Asia because of increasing human pressure on coastal marine environments also accompanied by water pollution.

Appropriately dimensioned shellfish culture has been shown to have little effect on the benthos (Fabi, Manoukian and Spagnolo, 2009), even when large areas are cultivated (Zhang *et al*., 2009). Bioextraction for top-down control of eutrophication symptoms has been documented in many parts of the world (e.g. Xiao *et al*., 2007), and it is clear that the presence of significant levels of shellfish aquaculture (e.g. in the People's Republic of China) has been instrumental in controlling coastal eutrophication, probably on a national scale (Sorgeloos, 2010). In addition, integrated multitrophic aquaculture (IMTA) has long been practised in Asia, and is an important farming system in the People's Republic of China. Currently, the interest in co-cultivation across trophic levels, as represented by IMTA systems, is growing in the European Union and North America. The focus, once again, is more on optimal production in developing countries, whereas in developed countries the emphasis is on reduction of emissions. There is a clear link between the two because, for instance, hypoxic pond water is not only an external environmental liability but also an internal factor of increased mortality.

The issue of site selection and carrying capacity can be complicated further as natural resources overlap political boundaries, for example, aquaculture within the Mediterranean. The Mediterranean Sea is shared by 21 countries with different cultural traditions, economic structures, societal profiles and legislative frameworks; therefore, a strategy aiming at multinational cooperation, exchange of information and harmonization of regulations that becomes successful here is likely to be a model for other regions of the world. Consequently, both FAO and the General Fisheries Commission for the Mediterranean have promoted initiatives to assist cooperation for the development of aquaculture and to enhance the dialogue among Mediterranean States and stakeholders regarding main issues, including site selection and carrying capacity (FAO, 2011).

Because there is little or no consensus among stakeholders – and often between countries – to set acceptable ecological aquaculture impacts, it is important to ensure harmonization of aquaculture regulation. There are different mechanisms. One of them is to define acceptable impacts by establishing criteria and variables to be used for estimating carrying capacity (IUCN, 2009). Another tool is the use of variables related to environmental quality or standards, for instance, primary production and sediment oxygen levels. In any case, the application of soft law instruments must be considered as an important element of environmental standards harmonization. Finally, it is important to overcome the *site-by-site* regulation process. Decisions on site selection are made on an individual basis in response to applications for tenure (McDaniels, Dowlatabadi and Stevens, 2005). This mechanism ignores the fact that many of the major concerns involve regional or subregional cumulative impacts beyond political boundaries. The question about size and distribution of aquaculture activity can be neither answered by considering local, site-by-site criteria nor by a process that is reactive rather than proactive. The problem of siting criteria has to be dealt within region-wide planning through appropriate regulations aimed to address cumulative impacts related to production, environment and social aspects.

Further region-wide planning should be implemented to assess cumulative impacts. Region-wide analysis of carrying capacities and impacts at a large scale can be expensive; however, the use of predictive models and modelling is most often needed in order to assist with decision-making. Models have the capability to be used at local, regional and international level, and are extremely valuable tools for aquaculture development and management.

Estimating aquaculture potential (i.e. physical carrying capacity) is a first step towards planning for aquaculture development. Continental studies of potential for inland fish pond farming were carried out for Latin America (Kapetsky and Nath, 1997) and Africa (Aguilar-Manjarrez and Nath, 1998). A regional study for the Caribbean using the same approach was carried out by Kapetsky and Chakalall (1998).

Data requirements

The information needed for site selection and estimates of carrying capacity is varied and will usually consist of data describing the physical, biological, economic, social and infrastructural aspects. These data can come from a variety of sources, ranging from primary data from the field or satellite imagery to all forms of secondary data, including paper maps, photographs and textual databases. Sources such as satellite imagery are already in digital form, although other sources may require some work to prepare them for use, for example, when they are to be used in a spatial database.

Clearly, data requirements and the mix of relevant variables will differ with location, species, farming system and social and cultural issues. With the exception of archived digital data and satellite imagery, it can be extremely costly and time consuming to collect field data first-hand, and, for this reason, it is often useful to locate the required data from existing secondary sources, either in paper or digital form. A primary consideration is to identify what data are really needed specifically to model the activity in question, as distinct from the plethora of data that may be available. This is followed by attempts to source the data and considerations regarding age, scale, quality and relative cost.

It can often be the case that estimating one variable from another can create new data that are more useful than the original data. Such data are referred to as "proxy" data, and established relationships may exist for deriving useable output from these data. Examples of aquaculture site selection proxies are: calculation of probable water temperatures from air temperatures, extraction of semi-quantitative soil texture from FAO soil association distribution maps, calculation of maximum dissolved oxygen levels from digital elevation models, and temperature data or calculation of maximum wave heights from wind direction, velocity and fetch (Aguilar-Manjarrez and Nath, 1998; Scott, 2003).

Establishing social and economic data requirements can be challenging, especially considering the less clear boundaries for the relevant stakeholders and the diverse nature of socio-economic issues related to the siting and farming activity. Information, such as available workforce, land ownership, access, water use, local infrastructure, local income, availability of housing and schools if the farming zone is far from urban areas, can be needed (also see EAA guidelines, FAO, 2010).

Data matrices

It would be useful to have guidelines for the range and quality of data required to form decisions, either for site selection or for carrying capacity. As previously noted, while a core data set may be identifiable, it will vary in detail based on local priorities and circumstances. Any such listing can only be indicative, identifying key parameters, and needs to be responsive to changes in context and real objectives. Table 3 shows an example of a data matrix that gives guidance on variables needed to address the four categories of carrying capacity in different farming systems; clearly, this matrix could be substantially extended to include many different farming systems and location-specific variations.

TABLE 3
An example of some data requirements for different farming systems. The lists of parameters are indicative rather than exhaustive

Farming system	Physical carrying capacity	Production carrying capacity	Ecological carrying capacity	Social carrying capacity
System 1: Coastal marine cages	Wind Waves Currents Depth Temperature Salinity Infrastructure Etc.	Temperature Salinity Diet type Feed regime Investment costs Markets Etc.	Critical habitats Biodiversity Eutrophication indicators EIA data in general Visual impact Etc.	Sea and coastal access rights Access to capital Beneficiaries Workforce Etc.

Farming system	Physical carrying capacity	Production carrying capacity	Ecological carrying capacity	Social carrying capacity
System 2: Ponds (inland/ coastal)	Water quantity Water quality Slope Soils Rainfall Evaporation Infrastructure Etc.	Temperature Diet type Feed regime Infrastructure Investment, costs Markets Etc.	Critical habitats Biodiversity Eutrophication indicators Visual impact EIA data in general Etc.	Land ownership, Water and riparian rights Access to capital Workforce Beneficiaries Etc.
System 3: Freshwater cages	Wind Waves Currents Depth Temperature Salinity Infrastructure Etc.	Temperature Infrastructure Investment, costs Markets Etc.	Critical habitats Biodiversity Eutrophication indicators Visual impact EIA data in general Etc.	Land ownership Water and riparian rights Access to capital Beneficiaries Etc.
System 4: Hatcheries	Water quantity Water quality Infrastructure Etc.	Temperature Diets Infrastructure Investment, costs Markets Etc.	Critical habitats Biodiversity Eutrophication indicators Visual impact EIA data in general Etc.	Local needs Land ownership Water rights Workforce Skills availability Visual impact Etc.
System 5: Bivalve culture	Wind Waves Currents Chorophyll and productivity Depth Temperature Salinity Etc.	Temperature Salinity Chlorophyll and productivity Investment, costs Markets Etc.	Critical habitats Biodiversity Bottom anoxia indicators Visual impact EIA data in general Etc.	Sea rights Access to capital Workforce Beneficiaries Etc.
System 6: Seaweed culture	Wind Waves Currents Nutrient content Depth Temperature Salinity Etc.	Temperature Salinity Nutrients availability Investment, costs Markets Etc.	Critical habitats Biodiversity Visual impact EIA data in general Etc.	Sea rights Access to capital Workforce Beneficiaries Etc.

The priority assigned to a given carrying capacity category will probably vary with location, depending upon national or regional priorities as well as environmental, cultural and social issues. There is, thus, probably no obvious, single, preferred sequence of development of these four categories. In fact, each category can be used as a free-standing decision- support tool for carrying capacity, and important decisions may be possible based upon a single component. Whatever the chosen sequence, it may be that decisions that can be extracted from the locally highest-priority category will determine the necessity, or otherwise, for other work to follow.

Decision-making and modelling tools

Assessment of carrying capacity for aquaculture can be challenging because of the number and nature of interactions, processes and scenarios involved. McKindsey *et al*. (2006) noted the potential complexity of the decision framework and surmised that many kinds of expertise may be needed to evaluate carrying capacity. They proposed that expert systems are the most practical and cost-effective way to manage the decision support process.

Decision support for expansion and optimization of aquaculture operations can make use of a wide range of models, drawing from a considerable volume of work (see, for example, www.ecasatoolbox.org.uk). Virtual tools, including mathematical models,

are becoming more effective in analysing the various components of carrying capacity and, therefore, in assisting sound decision-making on sustainable development of aquaculture without the costs of social experimentation. Ferreira *et al.* (2012) defined virtual technology in this context as "any artificial representation of ecosystems that support aquaculture, whether directly or indirectly". Such representations are designed to help measure, understand, and predict the underlying variables and processes, and they help to inform an ecosystem approach to aquaculture.

Virtual technology and models are an important part of decision support as they can be used to simplify or replicate existing processes easily and efficiently. These models can then be used to predict the potential consequences of different scenarios that could be expensive, challenging or dangerous to simulate in the real world, such as for example the release of a toxic chemical into the environment. Furthermore, modelling tools, such as "fuzzy" expert systems, can enable modelling where there may be inadequate data sets or uncertainty about boundaries. Fuzzy analytical techniques are available in GIS as parts of decision support systems (e.g. IDRISI by Clark University and Manifold™ by CDA International Ltd), but they require expert knowledge in order to take informed decisions about uncertainties. Self-learning systems have been used to combine 3D hydrodynamic and fuzzy decision models, presented in a GIS framework, to produce a validated classification of coastal environments that are particularly vulnerable to aquaculture development in terms of nutrient waste (Moreno Navas, Telfer and Ross, 2011).

Although site selection and carrying capacity assessment are complex issues, decision support tools can be used to represent all of the key components. The planning process should flow from a broad assessment of carrying capacity to detailed site selection, focused on a narrower spatial scale and supporting specific licensing procedures. A general approach for shellfish culture, from Silva *et al.* (2011), is presented in Figure 5. At all stages of the process, virtual technologies are valuable for decision support, providing a means to evaluate trade-offs among social, environmental and economic components of sustainability.

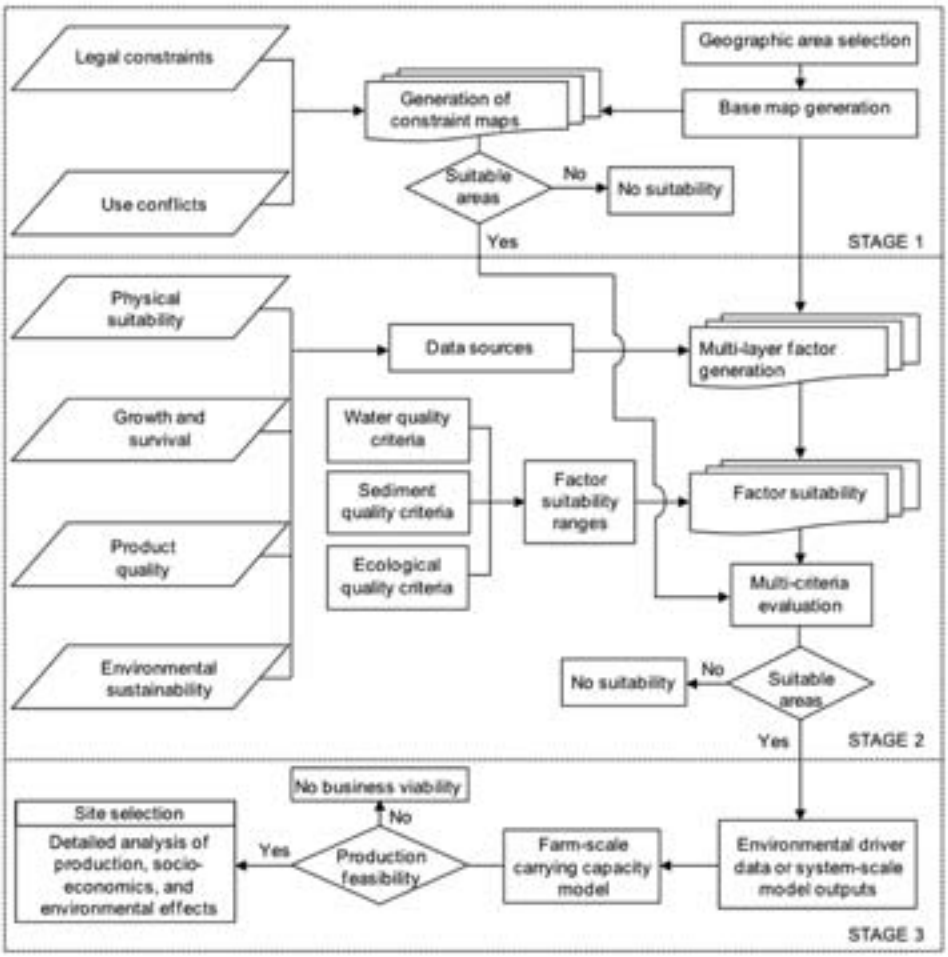
It is clear that virtual technologies, whether they are GIS, satellite remote sensing, dynamic models or others, can play an important role in addressing the physical, production and environmental components of site selection and carrying capacity. However, models need to be more production and management oriented, and need to adapt to local realities and conditions. This requires a more effective linkage between industry and research to create objective-led demand for virtual technology-driven research and technology development and a clear view of the business models that might support it.

Attention is drawn to virtual applications that include carrying capacity as one of their functions, or that have carrying capacity estimates as an objective. Some of these incorporate multiple models, multiple species, and the possibility that they could be adapted to contribute to broad-scale applications such as the global study of mariculture potential (Kapetsky and Aguilar-Manjarrez, 2012), or when applied at the national level as part of a broad process of estimating aquaculture potential. Several such applications, including, for example, blue mussel ecological carrying capacity (Filgueira and Grant, 2009), farm-level shellfish models for decision support to industry (Dallaghan, 2009), and using the FARM siting and decision model in data-poor situations (Ferreira, Hawkins and Bricker, 2007) have already been recognized as important examples and case studies of virtual technology by Ferreira, Ramos and Costa-Pierce (2012).

Environmental models

Environmental models are essentially tools, based on mathematical algorithms, that enable predictions of environmental changes and their consequences (Ford, 1999) using

FIGURE 5
General top down approach for carrying capacity assessment combining GIS and dynamic modelling



Source: Silva *et al*. (2011).

baseline and subsequent monitoring data. Such models are also used in aquaculture for farm management to simulate the quality of the water within the farming system to help minimize fish (or other farmed organism) deaths and to predict profitability (Beveridge, 2004). Models can range from simple mathematical calculations to the more complex integrated processes that require specialized software.

One of the earliest and simplest applications of modelling to aquaculture was Dillon and Rigler's modification of Vollenweider's original model, which used phosphorus (P) levels to estimate the ecological carrying capacity of freshwater lakes, assuming that P limits phytoplankton growth and therefore eutrophication (Beveridge, 1984). Thus, there would be a maximum P intake a lake could receive before the eutrophication process is triggered. This model has been used widely to estimate carrying capacity of lakes to support fish farming, for example, in the Republic of Chile. Further modifications of this model have also been used assuming nitrogen as the limiting element (Soto, Salazar and Alfaro, 2007).

A common method used for basic modelling is the mass balance equation, which can be used for many different parameters but is most widely used in a water quality context to model nitrogen and phosphorus concentrations in and from aquaculture systems. When using such models there has been an all-encompassing approach to their implementation through application of general guidelines. However, it is now clear that these general guidelines are not relevant for every system (Panchang, Cheng

and Newell, 1997); for example, site suitability for net pen culture should be modelled and considered on a site-by-site basis because environmental variability can make a general approach invalid (Dudley, Panchang and Newell, 2000). Consequently, it is important that the available data are representative of the system selected to prevent any restrictions on the model's usefulness (Cromey, Nickell and Black, 2002; Cromey *et al.,* 2002).

In the 1990s, determinations of carrying capacity for cage aquaculture were made using statistical models based upon empirical data (Beveridge, 1996). The driver for determinations of carrying capacity was an increased concern about the environmental effects of cage aquaculture in smaller, enclosed, poorly flushed waterbodies. This was due to impacts of nutrients and waste feeds not only on pelagic and benthic ecosystems, but also due to increased user and other social conflicts. Such increase in environmental-social concerns over the sometimes poorly planned and weakly regulated expansion of cage culture occurred in response to events, such as the "boom and bust" cycles of cage aquaculture in the Republic of the Philippines (Laguna de Bay and the seven lakes of San Pablo; Beveridge, 1996), in Indonesian reservoirs (Costa-Pierce, 1998), and in trash-fish-fed cage culture in many Asian countries (Pullin, Rosenthal and Maclean, 1993).

Over the past decade, numerous simulation models have been developed to predict environmental changes with different nutrient loadings from dissolved and particulate inputs from fish cage aquaculture (Byron and Costa-Pierce, 2012). Models such as DEPOMOD (Cromey, Nickell and Black, 2002; Cromey *et al*., 2002) and others (for example, Corner *et al*., 2006; FAO, 2009) can be used in local-scale assessment of the effects of fish cages on the environment. These models use information on depth, current velocity, current direction, feed input and farm management practices to predict the deposition of wastes from the cages. In Scotland, DEPOMOD is also used by the regulator to assess the environmental impact of new lease applications for salmon farms, supporting site selection at a local scale.

Mathematical models can be further developed into dynamic models that show change over time at a particular location, and are either coded directly to form a free-standing, single objective, often a commercial software product (Table 4), or may be developed within modelling environments, such as STELLA® or VENSIM® (Table 5). The latter offers a flexible and consistent approach to modelling, giving the opportunity to develop a range of models that can be easily disseminated and used while allowing further model development and adaptation by other users.

TABLE 4
Summary of environmental models and model systems relevant to aquaculture

Model	Type	Language/ environment	Reference
Simple mathematical models	Simple mass balance for nutrients and water exchange	Excel, etc.	Beveridge and Phillips, 1993
DEPOMOD	Waste dispersion (salmon cages)	Visual Basic	Cromey, Nickell and Black, 2002; Cromey *et al.*, 2002
COD-MOD	Waste dispersion (cod cages)	Visual Basic	Cromey, Nickell and Black, 2002; Cromey *et al.*, 2002
MERAMOD	Waste dispersion (Mediterranean cages)	Borland Delphi 7	SAMS, 2004
FARM	Resource management for shellfish	STELLA®	Ferreira, Hawkins and Bricker, 2007
APEM	Environmental ecosystem dynamics	STELLA®	Culberson and Piedrahita, 1996

Model	Type	Language/ environment	Reference
IAAS	Environmental ecosystem dynamics	STELLA®	Jamu and Piedrahita, 2002a and 2002b
AWATS	Waste transport (fish cages)	Various	Dudley, Panchang and Newell, 2000
MMFA	Material flow	Spreadsheet, e.g. Excel	Schaffner, Bader and Scheidegger, 2009
SWAT	Water quality/ groundwater modelling (inland aquaculture)	Visual Basic	Spruill, Workman and Taraba, 2000
EcoWin2000	Ecosystem model (offshore aquaculture)	EcoWin2000 software	EcoWin2000 Web site, 2010
MOM	Environmental impact model (coastal fish and shellfish)		Hansen *et al.*, 2001
KK3D	Deposition (tuna/Sea Bream)	C++	SAMS, 2004 (ECASA Web site)

TABLE 5
Examples of modelling environments

Model package	Date	Type	Web site
Dynamo	1960	Stock and flow (originally developed for business)	No longer in use
WASP	1983	Dynamic compartment modelling system	United States Environment Protection Agency (www.epa.gov/athens/wwqtsc/html/wasp.html)
Spreadsheets	1985	Cell based	Microsoft Excel
STELLA®	1985	Stock and flow	Isee Systems (www.iseesystems.com)
Ecopath with Ecosim (EwE)	1990	Static and dynamic modelling with a spatial aspect	NOAA (www.ecopath.org)
VENSIM®	1991	Stock and flow	Ventana Systems Inc. (www.vensim.com)
Simile	2002	Stock and flow	Simulistics (www.simulistics.com)
Powersim	2002	Stock and flow business simulation	Powersim (www.powersim.com)

With few exceptions (e.g. CADS_TOOL, which makes economic predictions from site specific data), all of the main aquaculture modelling tools remain focused on providing information and predictions on how the environment would respond to various siting and production levels for fish culture. In any aquaculture system, production is of great significance, and it is important to relate this to carrying capacity of a given system. However, there are relatively few production models that specifically address carrying capacity (Table 6). Most scientific work to develop tools that provide information to measure the carrying capacity of fish cage aquaculture appears to have only informed discussions of production and ecological carrying capacities. It must be noted, however, that many companies have their own models based principally around fish growth, feed

inputs, etc. These are frequently Microsoft Excel models that may have been customized for internal use. Several other customized Excel models are also available, although the AquaFarm model is coded in C++ and CADS_TOOL is coded in Java®.

TABLE 6
Examples of production models relevant to aquaculture

Model	Functions	Reference
AquaFarm	Oregon State University. Developed from the original POND model, this provides: • simulation of physical, chemical and biological unit processes; • simulation of facility and fish culture management; • compilation of facility resource and enterprise budgets; • a graphical user interface and data management capability.	Ernst, Bolte and Nath, 2000
CADS_TOOL	Cage Aquaculture Decision Support Tool is designed to help cage aquaculture managers optimize their choice of sites for placement of cages. Specifically, it will: • classify a site; • select the best site from several alternatives; • calculate the sustainable holding density of a chosen site; • perform a basic economic appraisal of a site.	http://www.aims.gov.au/en_GB/docs/research/sustainable-use/tropical-aquaculture/cads-tool.html
FARM	Assessment of coastal and offshore shellfish and finfish aquaculture at the farm scale. It provides: • prospective analyses of culture location and species selection; • ecological and economic optimization of culture practice for shellfish and finfish; • timing and sizes for seeding and harvesting, densities and spatial distributions; • environmental assessment of farm-related eutrophication effects.	Ferreira, Hawkins and Bricker, 2007
POND	Assessment of onshore fish and shellfish growth and production. It provides: • prediction of production and feed requirement; • optimization of seeding size and culture periods; • optimization of farming methods and environmental effects; • mass balance analysis.	Franco, Ferreira and Nobre, 2006
RDSS	Raceway design and simulation system. Allows calculation of fish growth, feed requirements and whether conditions are exceeded.	Wang *et al.*, 2008
Winshell	Model to determine individual shellfish growth for oysters, clams and mussels.	www.longline.co.uk/winshell

Spatial modelling for site selection and carrying capacity

The deployment of spatial planning tools for analysis, decision-making, modelling and data management is an essential element for the implementation of the EAA. Spatial analysis enables definition of boundaries relevant to carrying capacities, enhancement of existing ecosystem data by incorporation of data specific to the needs of aquaculture, and integration and analysis of the environmental, administrative, social and economic components of the ecosystem. Defining ecosystems and production systems spatially is essential to the EAA to raise the awareness of aquaculture planners and practitioners to issues that must be taken into account for the further development of aquaculture and for the mitigation of the potential impacts of aquaculture on the environment.

Geographic information systems are spatial modelling frameworks designed for use at different scales, as they can provide both general and site-specific information and investigate issues at both local and waterbody or watershed scale (Silvert and Cromey, 2001). GIS is particularly useful as an environmental management tool because the system organizes, analyses and presents geographical data in a useful and efficient

manner using standard data formats. In terms of aquaculture development, the advantage of GIS is that the impact from several farms could be analysed on a larger scale (aquaculture zone, waterbody), as well as taking into account inputs from other sources; therefore, the results are truly representative of the activities taking place in the area and the subsequent environmental conditions.

GIS has become increasingly important to aquaculture since its introduction in the late 1980s, and projects using GIS and remote sensing have become more diverse in the species and areas studied in addition to the overall purpose and impact of the research. GIS allows the simultaneous investigation of multiple sites, and, consequently, it is a highly suitable tool in aquaculture site selection and planning projects (Valavanis, 2002), which were among the first applications in the aquaculture sector, with Meaden (1987) looking at potential sites for trout farms in the United Kingdom of Great Britain and Northern Ireland, and Kapetsky, Hill and Worthy (1988) using GIS to identify suitable locations for catfish (*Ictalurus punctatus*) farms in Louisiana, the United States of America. As the use of GIS in aquaculture has increased so has the amount of research published, and some key studies have been published (Aguilar-Manjarrez, 1996; Kapetsky and Nath, 1997; Nath *et al.,* 2000; Kapetsky and Aguilar-Manjarrez, 2007; Ross, Handisyde and Nimmo, 2009; Aguilar-Manjarrez, Kapetsky and Soto, 2010; Meaden and Aguilar-Manjarrez, 2013).

McKindsey *et al.* (2006) noted the requirement for GIS support specifically for the physical and ecological carrying capacities. While many studies have used GIS for site selection, in more recent studies GIS has been used as an environmental management tool assessing waste dispersion and environmental impact (Corner *et al.*, 2006). Clearly, spatial analytical modelling tools are very easily extended to cover all four carrying capacity categories, as was outlined in an earlier FAO Expert Workshop (Aguilar-Manjarrez, Kapetsky and Soto, 2010).

Spatial models can also be used together with other models as part of an overall process to provide decision support for site selection and assessment of carrying capacity. This was highlighted in the Sustainable Options for People, Catchment and Aquatic Resources (SPEAR) project (Ferreira *et al.*, 2008b), which aimed to provide guidance to aquaculture administrators on sustainable carrying capacity in two areas in the People's Republic of China. Multiple models were used at different scales to assess the key processes and interactions between the main issues relevant to carrying capacity, including economical, environmental and management strategies. GIS was used throughout the project to provide the geographic context for key variables used in modelling, as a platform for communication between different model components, in verification, and for visualization and spatial analyses of model results. The combination of dynamic modelling and GIS is also exemplified well in the EU FP7 Sustaining Ethical Aquaculture Trade project (SEAT, 2012).

It is important to acknowledge that spatial models are not solely used by scientists and others with technological backgrounds. They can have an important practical influence on day-to-day business operations, such as aquaculture and agriculture, where the majority of stakeholders, farmers and producers do not have sufficient mathematical or scientific backgrounds to understand the modelling complexities. Fortunately, GIS can be used to simplify the process, and web-based spatial systems are becoming more prevalent. The Norwegian based AkvaVis application is an example of a Web-based interactive decision support system that allows users to identify suitable locations for salmon and mussel farms using simple queries that highlight potential issues and constraints, such as the proximity to other farms and depth of the site (Ervik *et al.*, 2008). Internet map servers and Web-based programmes are becoming more popular because they are an efficient way to share models and a valuable platform to test models with stakeholder participation.

Modelling socio-economic drivers

Modelling is primarily predictive and often used as a precursor to, and informant for, implementation of environmental management. There are also other methods used within the management framework that are not based on modelling and that are implemented during the production and post-production process, though these methods are necessarily informed by the ecological and production models and decision support systems presented earlier.

A key example of implementation of non-modelling and modelling approaches is when incorporating stakeholder input (Byron *et al.,* 2011). This has the premise that science is much more likely to be accepted if there are agreed upon, cooperative, aquaculture research frameworks that combine efforts of scientists and farmers and that are integrated into outreach and extension services. Here, the ecological carrying capacity results are adopted into management, and stakeholders have had direct input into and obtain an intimate knowledge of the science (Costa-Pierce, 2002). In this regard, efforts to improve methodologies for the determination of the social carrying capacity may be well served to consider approaches that integrate rigorous science into participatory extension processes that include and measure the quality of participation and stakeholder inputs (Dalton, 2005; 2006). Estimation of this will establish a more quantitative basis for discussion, integration of ecological, production and social implications and final decision-making, enabling a better understanding of the trade-offs of aquaculture production for a particular locality or set of conditions.

Little *et al.* (2012) not only noted the growing use of participatory approaches in EAA, but also noted that careful consideration must be given to who is encouraged and supported to participate, in what ways and for what specific purpose. Because participation has become an accepted orthodoxy in development circles and has attracted both mainstream and inevitable criticism (Henkel and Stirrat, 2001), greater reflection is required. Increasingly so-called participation is part of a box-ticking exercise within more blueprint approaches to standard approaches to development that have been done in the past. Community stakeholder engagement is frequently cursory, unrepresentative of marginal voices, and more consultative than collegiate. Often, expectations within "projects" are too narrowly sectoral and involve a tiny proportion of potential stakeholders in any active way. Community stakeholder engagement needs to be strengthened, with more rigorous application of cost–benefit analysis. Alongside immediate economic concerns, a broad understanding of the social and ecosystem services that are part of aquaculture and associated value chains must be considered. Identification and use of appropriate indicators can be a robust approach to assessing social impacts, and must pay equal attention to local conditions and opinion if they are to be accurate and relevant in their application. Project scope and identification of stakeholders have rightly been identified as key steps. The boundaries around EAA are typically set too narrowly and the resources applied too limited and/or conservatively for what are complex *human* systems. This often brings these non-modelling approaches into conflict with modelling tools, as by necessity the latter simplifies the system into sectors for which numerical estimations can be made to produce generic models.

Field verification

Field verification as part of modelling work is absolutely essential, both for quality control of certain data sources and for testing the outcomes of models. While an environment and an activity can be modelled in total isolation as an academic exercise, it is only through careful verification that the general applicability of results can be ensured. Consequently, decisions on site selection and carrying capacity achieved through modelling require field verification, which should include participative input from stakeholders. This not only refines the data inputs and the model outcomes,

but also provides feedback into the modelling process itself by allowing better understanding of the assumptions used. It is important to recall that models generated with participative input also have high acceptability to the full community.

Implementation of carrying capacity concepts

McKindsey *et al.* (2006) and the International Council for the Exploration of the Sea (ICES, 2008) identified gaps in knowledge that need to be addressed in order to advance progress in the scientific basis of carrying capacity for aquaculture, including:

- Development of specific guidance to better define "unacceptable" ecological impacts that include stakeholder identification of important ecological attributes and ecosystem components.
- Identification of critical limits (i.e. performance standards or thresholds) at which the levels of aquaculture developments disrupt an ecosystem, thus requiring management actions.

These indicators, often known as environmental quality standards (EQSs), are used by regulators and decision-makers and employ best available science and often adopt a "precautionary approach" in their implementation. The existence and use of standards as part of the environmental management of aquaculture, to inform regulation, for enforcement, environmental impact assessments (EIAs) and other procedures is highly variable. In many countries, water quality standards are well developed, and a considerable amount is known with regard to the local ecosystem and aquaculture production. In Europe, they are now being applied in relation to particular waterbodies, while in some developing countries water quality standards have sometimes been copied from developed countries and may not reflect local conditions or needs. The Association of Southeast Asian Nations has also initiated the process of standardizing water quality standards within the Southeast Asian region. Implementation of such standards also depends upon effective governance and control mechanisms for implementation within aquaculture and environmental management (Telfer and Beveridge, 2001). Different countries, regions and even localities may use location and system-specific indicators of change, which are implemented as part of the initial regulation of the development or for continued monitoring of environmental and production "health". Use of such indicators for monitoring and governance of aquaculture have been critically reviewed (FAO, 2009).

In many countries, an EIA is required as part of the licensing process for farms over a threshold size or if an existing site expands beyond its approved licence size. The EIA may be defined as "The process of identifying, predicting, evaluating and mitigating the biophysical, social, and other relevant effects of development proposals prior to major decisions being taken and commitments made" (FAO, 2009). The EIA most often provides the framework for the implementation of environmental carrying capacity criteria, although it can also include social and economic impacts. However, the practical implementation of these may be weak, as there are not yet enough sector studies and fully agreed indicators (FAO, 2009).

An EIA for single aquaculture farms may or may not use direct evaluations of carrying capacities or good acceptable proxies (e.g. models). Conversely, when dealing with many small farms that often do not formally require an individual EIA, there is a need for a strategic environmental assessment (SEIA) to ensure that the sum of the small farms will not exceed the ecological carrying capacity; however, this is as yet rarely done. This can also be the case even for large farms sharing a common waterbody, for example, for shrimp farming in coastal zones. Although in most countries each farm requires an EIA, the combined effects of farms on the receiving waterbody (e.g. a mangrove estuary) is normally not assessed or monitored, meaning that joint farm nutrient loads can exceed the ecological (and sometimes social) carrying capacity. This may also be true for cage farming, for example, in the Republic of Chile (Soto and Norambuena, 2004).

Indicators for carrying capacity are less easy to implement in areas with variable or little governance. In such areas indicators require particular adoption by local aquaculturists, and therefore should be of particular relevance to their own particular system.

TROPECA, a project sponsored by the Department for International Development of the United Kingdom of Great Britain and Northern Ireland, addressed the issue of relevant indicators of environment-based carrying capacity in the People's Republic of Bangladesh and the Socialist Republic of Viet Nam using a participatory approach. Indicators developed were easily assessed and measured using simple equipment or parameters, though the ranges and thresholds for these indicators were validated through scientific investigation (Hambery *et al.*, 2005). The project developed an approach for user-led aquaculture development, including site selections and management, through the use of these non-modelled indicators (Hambery, 2005). The development and use of such indicators should be based on a synthesis of top-down "expert" and local "bottom-up" opinion (Bell and Morse, 2008). Indicators should also enable a robust baseline of social impacts to be built and to be a solid basis for further understanding changes over time. While site specific, some indicators are more generic and should also be able to allow comparison between sites and systems. Indicators can also be specific for the four categories of carrying capacity, and can be applied through a range of models for implementation of these categories (see Table 7).

TABLE 7
Examples of indicators for the four categories of carrying capacity with some appropriate modelling tools

Category (pillar)	Indicators	Measures/ approaches	Models/tools
Physical	Water availability Water access Water quality (including chlorophyll and primary productivity in the case of extractive species) Hydrography Hydrodynamics	Inventory of aquaculture Site selection Zoning Water management Integrated coastal zone management Climate change Risk assessment Transboundary waterbodies/ watersheds	GIS, e.g.: ArcInfo (ESRI®) IDRISI™ (Clark Labs) MapInfo™ (Pitney Bowes) GRASS (grass.fbk.eu) Google Earth (earth.google.com) Surfer™ (Golden Software)
Production	Intensity of production Yield Investment Market value Economic indicators	Optimization Management Area management Cluster management	POND (www.longline.co.uk) FARM (www.longline.co.uk) Winshell (www.longline.co.uk) INVESTMENT (FAO model) Many proprietary model options (e.g. operated by aquaculture companies)
Ecological	Waste dispersion Habitat deterioration Biodiversity and indicator species Dissolved nutrients Eutrophication Benthic hypoxia	Monitoring Risk assessment Biodiversity and exotics Resource (e.g. habitat) mapping	DEPOMOD (Cromey, Nickell and Black, 2002; Cromey *et al.*, 2002) STELLA™ (www.iseesystems.com) Vensim® (www.vensim.com) Powersim™ (www.powersim.com) GIS (see above)
Social	Space conflict Employment and household income Livelihood Acceptability Value to the community West: regulation East: flexibility	Participatory Transparency Advocacy Identify stakeholders	Based on perceptions May be non-quantitative

Source: Modified from Ferreira *et al.* (2012).

Groffman *et al.* (2006) have identified ecological threshold as the point at which there is an abrupt change in an ecosystem quality, property or phenomenon, or where small changes in an environmental driver produce large responses in the ecosystem. On the other hand, thresholds may also be defined in a legal framework as the point beyond which pollution load becomes unacceptable. This threshold defines the legal boundary between acceptable contamination and unacceptable pollution (Hassan, 2006). In this context, EQSs and environmental thresholds become the major prerequisite for estimating the carrying capacity of a fish farm in a given site and also necessary for a meaningful EIA and environmental monitoring.

EQSs set concentrations in the environment for certain compounds below which unacceptable effects are expected not to occur (IUCN, 2009, FAO, 2009). One problem of setting standards is that not all of them are legally enforceable, and many are fixed in guidelines that usually embody political commitments rather than legally binding obligations. Moreover, as the establishment of these standards implies that something is defined by policy-makers rather than by scientists, it is important to ensure harmonization and reduce the arbitrariness of the authority. Clearly, compromise among the different interests and stakeholders is required, as development within carrying capacity requires not only environmental and scientific requirements but also social and political acceptance. In this context, soft law instruments must be considered as an important element of harmonization of legally enforceable standards.

The definition of social carrying capacity indicators is much more challenging. They can involve indicators of local conflicts, employment, alcoholism, women, child labour, etc., and may vary from locality to locality. While the definition of critical limits for ecological carrying capacity has been explored to some extent (e.g. level of phosphorus that will trigger eutrophication), the definition of critical limits for social change and indicators have not been fully defined in the context of aquaculture. According to Little *et al.* (2012), critical limits and indicators should be produced within the broader producer community and should be ideally monitored over time and/or matched with otherwise similar communities where aquaculture is not established as a major activity. This approach would allow identification of the depth and spread of impacts within communities in which aquaculture is established, either through direct participation as producers or indirectly through employment or linkages within the economy. Beyond the immediate net benefits, they should also indicate whether aquaculture, once established, supports or detracts from equity within the community. These indicators should include: (i) proportion of households within the community that gain some benefit(s) from aquaculture; (ii) evidence for complementarity within the livelihood portfolio; (iii) trend of increasing median incomes of all households in the community where aquaculture is practised; (iv) low standard error of the mean for monthly household incomes in aquaculture communities; and (v) increasing trend in day labour rate (both in aquaculture and non-aquaculture related activities (Faruque, 2007).

National regulators worldwide should implement aquaculture carrying capacity regulation with full consideration of more than just emission standards or EQSs. This would allow establishment of different categories of sites and identification of areas that are likely to be acceptable for aquaculture development. Because there is no consensus among stakeholders and countries to set acceptable ecological aquaculture impacts, it is important to ensure consistent regulation. It is also important to avoid regulation on a *site-by-site* basis where decisions on site selection are made on an individual basis in response to applications for tenure (McDaniels, Dowlatabadi and Stevens, 2005). This mechanism ignores the fact that many of the major concerns involve cumulative impacts at the waterbody scale. Questions about size and distribution of aquaculture activities can neither be answered by considering local, site-by-site criteria nor by a process that is reactive rather than proactive. Instead, siting criteria are better if managed through region-wide planning and based upon regulations appropriately aimed to address cumulative impacts.

Conclusions

The use and implementation of the carrying capacity concept within the EAA can be highly complex, and a number of considerations must be taken into account. One of the most difficult problems to overcome is the difference in nature of what carrying capacity actually means in the context of aquaculture and its development. The classification of the types or categories of carrying capacities described by McKindsey *et al.* (2006) for shellfish culture is a useful interpretation of carrying capacity, but their implementation in general aquaculture practice and development must also be able to allow for systems where species are simple consumers (e.g. molluscan shellfish, seaweed), those which are fed from external sources but are net contributors into the environment (e.g. carnivorous fish, shrimp), or mixtures of both systems. Equally, the four categories of carrying capacity will be implemented differently depending on local conditions and requirements for these species and issues of local regulation and governance. This leads to the necessity of implementing these categories of carrying capacities differentially according to weightings relevant to the species, systems and locality.

The implementation of the EAA based upon application of carrying capacities will therefore require a defined system of weighting factors, leading to a series of questions:

1. What are the relative weightings for the different combinations of species, farming systems and localities?
2. Can rules be developed to decide these relative weightings of the four categories under a range of circumstances?
3. Can these rules be defined generically in a single system, which forms the basis for implementation of the four categories throughout the world?
4. Can these weightings be incorporated into the existing regulation and governance of aquaculture in the different localities, or should they inform these for the future?

Implementation and measurement of the effectiveness of the four categories, in answering the questions above, will be dependent on specific indicators for collection of baseline or subsequent monitoring data. As with the capacity categories, these indicators may vary depending on the system, location and governance. These too will need careful consideration as to their implementation and relevance to a particular aquaculture system and locality.

There are a number of methods and/or generalizations that can be used to weigh both the carrying capacity categories and their indicators. One such example is that suggested by Gibbs (2009) for marine mollusc culture in New Zealand. Here, the approach did not include the physical carrying capacity as a particular category, but begins the development process with an initial site selection using the measures and models implicit in the physical carrying capacity category. Then, once the potential for aquaculture is established, the other categories can be differentially applied depending on the weightings discussed above. An example of this weighting is given in Ferreira, Ramos and Costa-Pierce (2012). In addition to the remaining categories of carrying capacity, Gibbs (2009) introduced "economic capacity" as the biomass at a particular location for which investment can be secured. This brings in an additional element probably considered under the initial four categories within the production capacity category.

Some form of EIA is required as part of the aquaculture licensing process in many countries, and the future implementation of carrying capacity criteria could be built within these EIA systems. In addition, to ensure a more effective ecosystem perspective, it is often necessary to go to a higher level strategic planning and management framework, including SEIA, and in many cases connecting the estimation of carrying capacity to risk assessment.

These issues, and the need to weigh carrying capacity categories relative to each other, will be further developed and refined as part of the *FAO Guidelines* for implementation of the EAA using a carrying capacity approach.

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Key drivers and issues surrounding carrying capacity and site selection, with emphasis on environmental components

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Abstract

Historically, site selection has been based largely on available space and constraints to productivity (e.g. circulation or food availability). However, in order to ensure sustainable development: (a) carrying capacity and site selection can no longer be viewed in such a limited way, and requires an analysis of trade-offs among production, ecology, governance, and social aspects; and (b) a system-wide assessment of carrying capacity should precede licensing at the farm-scale. This is in keeping with the three core principles of the Ecosystem Approach to Aquaculture that promote ecological balance, social equity, and multi-sectorial planning. This review considers the relevant legislation and regulations in the major world producers of aquaculture goods, and highlights the variable requirements for licensing, particularly with respect to the environmental component. Additionally, different countries and economic blocks view carrying capacity in different ways. In Southeast Asia and the People's Republic of China, production is generally the limiting factor, whereas in Europe and North America, social constraints are of paramount importance. Both aspects present a challenge for a common assessment platform with respect to carrying capacity and site selection.

Virtual technologies such as GIS, satellite remote sensing, and dynamic models, can play a huge role in addressing the physical, production, and environmental pillars of site selection and carrying capacity. However, models need to be more production- and management-oriented, and adapt to local realities and conditions. Research

into improved models for social aspects, and for the connection to environmental assessment models, needs a much greater effort. This will establish a more quantitative basis for discussion and for decision-making, enabling a better understanding of trade-offs. Distributed computing (e.g. smartphones) has great potential in bridging the information gap in many thematic areas, and should certainly be used to improve the understanding of aquaculture-environment interactions, simulate local conditions in real time, and interpret the outputs of sensors.

Aquaculture is particularly important to developing countries, where it is not only critical in supporting healthy food provision but is also an important source of income for local communities. It is important however that production in developing countries should not translate into negative environmental externalities considered unacceptable in the developed world.

Introduction

In the field of aquaculture, carrying capacity has been variously defined through its original meaning (Krebs, 1972; Kashiwai, 1995) which may be

$$\sum_{i=1}^{n} \frac{dB_i}{dt} = 0 \qquad \text{(Eq. 1)}$$

where: B_i = biomass of species i of n and t = time.

Eq. 1 suggests that in a stable community the *average* biomass of component species is asymptotic over the time period of interest, and corresponds to the logistic growth curve in population ecology.

The specific demands of aquaculture, an activity based on the interaction between humans and other elements of the natural system, converting the latter (at least in part) into a *managed* system, led to the definition of carrying capacity as "the standing stock at which the annual production of the marketable cohort is maximised" (Bacher *et al.*, 1998; Smaal *et al.*, 1998). Although this definition was proposed in the context of organically extractive open water culture (for bivalve shellfish), it is sufficiently broad to be relevant for production both in open off-the-coast and offshore environments and in land-based systems using ponds or raceways.

However, even from the point of view of sustainable production this definition needs to be qualified, because in economic terms the maximisation of annual production is not the objective function. This function seeks to achieve optimal *profit*, well before the inflexion point in the production function, where total physical product (TPP) maximises *income* (e.g. Jolly and Clonts, 1993; Ferreira, Hawkins and Bricker, 2007).

This simplistic view of carrying capacity for aquaculture based solely on production has developed over the last decade into a four pillar approach based on physical, production, ecological, and social carrying capacity (Inglis, Hayden, B.J. & Ross, 2000; McKindsey *et al.*, 2006). In large part these pillars encompass the three elements of sustainability, viz. planet, people, and profit. Recent legislative instruments such as the European Union's Marine Strategy Framework Directive (EU MSFD – EC, 2008), together with guidelines for an Ecosystem Approach to Aquaculture (EAA – Soto, Aguilar-Manjarrez and Hishamunda, 2008), highlight the ecological component and aim to optimize production without compromising ecosystem services. Part of the challenge of determining carrying capacity is the quantification of negative externalities as a first step towards improved management.

The social[1] pillar is at the forefront of decision-making in the EU, US, and Canada,

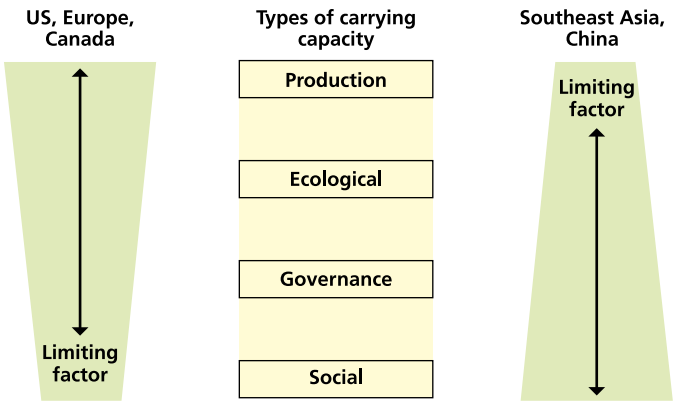
[1] Here used in the context of social opposition to visual or other impacts of aquaculture development, such as conflict with leisure areas.

and can frequently be identified as the single most important criterion for carrying capacity assessment and site selection (Figure 1). By contrast, in Asia and other parts of the world where food production is the paramount concern, licensing criteria are more frequently based on the physical and production pillars, with ecological and social considerations assuming less relevance.

Virtual tools, including various types of mathematical models, are fundamental in analysing these various components of carrying capacity, and therefore in assisting sound decision-making on sustainable development of aquaculture without the costs of social experimentation. Ferreira *et al.* (2010) have defined virtual technology in this context as:

Virtual Technology is defined as any artificial representation of ecosystems that support aquaculture, whether directly or indirectly. Such representations, exemplified by mathematical models, are designed to help measure, understand, and predict the underlying variables and processes, in order to inform an Ecosystem Approach to Aquaculture.

FIGURE 1
The relative importance of the four pillars of carrying capacity



Source: Adapted from Carrie J. Byron and Barry A. Costa-Pierce (2012).
Note: The narrowest segment for the regional areas corresponds to the greatest constraint to carrying capacity.

This review focuses on the key drivers and issues surrounding carrying capacity and site selection, with an emphasis on the environmental components, and aims to:

1. Examine current practice for site selection worldwide, both for inland (freshwater) and coastal (onshore, off-the-coast, and offshore) aquaculture;
2. Contextualise the existing approach in the light of environmental legislation in different parts of the world;
3. Analyse how carrying capacity and site selection can benefit from virtual technologies, and identify areas for development;
4. Recommend actions to promote an Ecosystem Approach to Aquaculture from an environmental perspective.

Worldwide perspective

Current global criteria and approaches for site selection

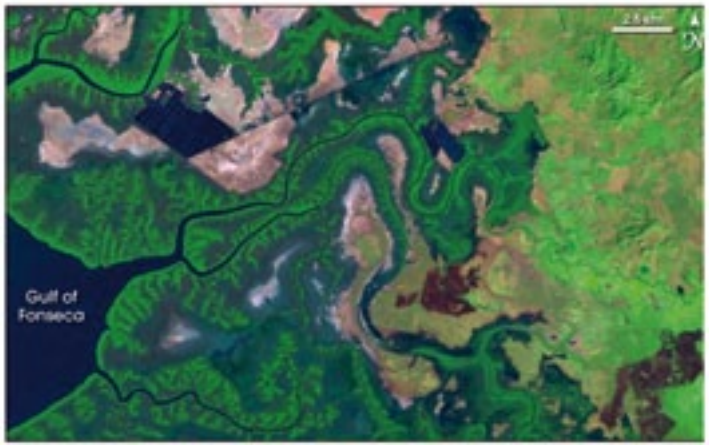
The establishment of aquaculture activities in different geographical areas has traditionally been a bottom up process, without a particular concern about overall definition of a zoning framework. This has been the case globally, from the development of salmon cage culture in Scottish lochs to the incremental destruction of mangroves in Nicaragua for construction of shrimp farms (Figure 2).

This approach to licensing (or in many cases just to development), based mainly on space availability and limits to production rather than on any environmental criteria led to a number of undesirable ecosystem effects, including habitat destruction both on land and in open waters, coastal eutrophication through increased nutrient loading from land, and organic enrichment of sediments and loss of benthic biodiversity.

Changes in the regulatory framework have in the last decades led to a more stringent approach to licensing, most notably in the European Union, United States, and Canada. Nevertheless, only in a few cases (e.g. Ferreira *et al.*, 2008b) has

FIGURE 2
Expansion of shrimp ponds over a 13 year period in Estero Real, Nicaragua

November 19, 1999



January 6, 1987

Source: Adapted from Byron and Costa-Pierce (2008).

there been a concern with the assessment of carrying capacity at the system scale, i.e. defining and quantifying potential *aquaculture zones*, as an initial step prior to local-scale licensing of aquaculture operations.

Mathematical models such as DEPOMOD Cromey, Nickell and Black, 2002; Cromey *et al.*, 2002) and others (Nath *et al.*, 2000, Corner *et al.*, 2006) have become increasingly important in supporting the local-scale assessment of effects on the environment, and are used e.g. in Scotland by the regulator in order to screen for environmental impact of new lease applications for salmon farms, i.e. to support *site selection* at the local scale.

The international legal framework

On a global scale, the Convention on Biological Diversity (CBD) is one of the most important documents concerning environment and biodiversity. Loss or alteration of habitats as a result of aquaculture operations can become a biodiversity concern when it changes the living conditions of other species, for instance through:

(i) seed collection for aquaculture from benthic habitats using destructive gear causes habitat destruction and/or alteration;
(ii) Spatial conflicts: aquaculture takes up space, often very large areas, not only in bays and oceans, but also on nearby foreshore areas as a result of development of aquaculture infrastructures;
(iii) destruction of tidal marshes and mangroves that serve as important nursery grounds for populations of fish and shellfish

However, the CBD has also recognized that aquaculture may have some positive effects, for instance by helping preserve biodiversity when, as a successful economic activity, it can provide a release to the predation pressure over commonly harvested aquatic species. Best site selection (including optimal flushing and dispersal of nutrients) could actually promote an increase of local and total productivity, especially in oligotrophic and mesotrophic systems, particularly when additional substrate heterogeneity, such as building of artificial reefs to soft bottom areas, is provided. Additionally, some forms of aquaculture, such as shellfish and macroalgal production, could contribute to biodiversity enhancement by providing habitat structure and food.

Several international conventions include provisions related to aquaculture e.g. the Oslo-Paris Convention (OSPAR), Bern Convention, and Helsingfors Convention (HELCOM). In addition, the European Community is committed to the principles of the Precautionary Approach, the guidelines for aquaculture in the FAO Code of Conduct for Responsible Fisheries (Article 9 of which covers Aquaculture Development) and other international arrangements or guidelines such as the ICES Code of Practice on the Introductions and Transfers of Marine Organisms.

The legal framework in the People's Republic of China and southeast Asia

Asia as a whole currently produces 90 percent of the world's aquaculture (Sorgeloos, 2010). It is estimated that the current annual production of 68 million metric tonnes (MMT) (De Silva, 2010) will need to be substantially increased to meet the world demand for aquatic products by 2050. This increase, of the order of 30 MMT/year (Swaminathan, 2010), will rely on aquaculture, and will not be provided by Europe or North America. In both cases, production is limited by stringent environmental regulation and social concerns. Growth in the European Union will be very limited, and the United States of America expects an annual increase of about 0.5 MMT (Olin *et al.*, 2010). This is a 30 percent increase of current United States of America production, but hardly registers on the scale of world food requirements. By contrast, the production of Vietnamese catfish in the Mekong Delta has increased exponentially over the last three years, with a current production of 1.2 MMT/year, and successful placement in the Europen and United States of America markets (De Silva, 2010).

As a consequence, it is important to review environmental legislation in the framework of aquaculture for the main Asian producers, to understand to what extent comparable constraints exist to aquaculture production in various parts of the world.

The European Union legal framework

Specific European legislation relevant to limiting the effects of aquaculture on biodiversity is less well established than for capture fisheries. Among the relevant legislation is that on aquatic animal health, and the Environmental Impact Assessment (EIA) legislation.

Most aquaculture concerns are regulated by national legislation which is influenced by a number of horizontal EU Directives governing water, habitat and bird life. Following from these directives it is required that developing projects, including new fish[2] farms, should be subjected to prior assessment if they are likely to have significant effect on the environment. In the framework of the reform of the Common Fisheries Policy (CFP) the European Commission recognized the importance of aquaculture and the necessity to develop a Strategy for the Sustainable Development of European Aquaculture (COM 2002 511 final). The Strategy set out a wide range of policy principles on which the future development of aquaculture in the EU would be based, including the necessity to assure that aquaculture becomes an environmentally sound activity. Additionally in the framework of the CFP a biodiversity action plan was developed which includes a chapter dedicated to impacts of aquaculture.

The second generation EU water directives, which presently consist of the Water Framework Directive (WFD 2000/60/EC) and MSFD, do not address aquaculture in a meaningful way. The WFD explicitly excludes the fisheries component, and only considers fish populations as a Biological Quality Element (BQE) in transitional waters.

The approach itself, with an emphasis on a *one out, all out* classification for quality elements in the determination of Good Ecological Status (GE_cS), has been described

[2] Although finfish are referred in the EU directive on environmental impact, the national authorities are free to interpret this as appropriate, so some Member States consider the legislation to apply to other types of aquaculture, based on areal occupation and production.

as a "deconstructing structural approach" (Borja *et al.*, 2010). The MSFD is developed in a holistic manner, defining eleven quality descriptors (QD) that should in some (as yet unknown) way be combined to establish Good Environmental status (GE_nS). QD3 is the Fish and Shellfish quality descriptor, but contrary to what might be expected, the guidance produced for this descriptor focused only on capture fisheries. It is disappointing that aquaculture is considered in the MSFD only as a pressure; discounting for instance the role that organically extractive aquaculture plays in top-down control of eutrophication symptoms in many European coastal areas.

Since the WFD mandates GE_cS by 2015 and the MSFD requires GE_nS by 2020, the latter for very large marine areas, extending to the Exclusive Economic Zone (EEZ) of the EU, aquaculture development in Europe is clearly under significant pressure with respect to environmental regulation.

The United States legal framework

This brief review of the legal framework in the United States of America has been largely drawn from Duff, Getchis and Hoagland (2003), Pittenger *et al.* (2007), Upton and Buck (2008), and from Peterson *et al.* (2010) in what concerns shellfish aquaculture.

In United States of America coastal waters the legal framework delegates jurisdiction to individual states, leading to complex results and inconsistencies. A comprehensive review of aquaculture regulations across the United States of America (the "Aspen Report" sponsored by the United States of America Fish and Wildlife Service) was carried out in 1981, and identified at least 120 federal laws directly (50 laws) or indirectly (70 laws) affecting aquaculture, together with over 1,200 state statutes regulating aquaculture in 32 states. According to this report, in some states aquaculture operations must obtain at least 30 permits to site and operate their businesses. Regulatory jurisdiction over bivalve mariculture typically requires approval by several local, state, and federal agencies.

Public land management typically falls under the authority of the state department responsible for environmental protection. Regulatory complexity is further increased when towns or counties are given jurisdiction over local waters. The consequences of this complexity on shellfish growers have often been an expensive, time-consuming, and sometimes unsuccessful process for obtaining permits (Duff, Getchis and Hoagland, 2003).

In response to concerns over real or perceived regulatory complexity, many states have designated a particular state agency as the "lead" and starting point for mariculture permit applications. Many coastal states also have created inter-agency coordinating committees or task forces to facilitate the mariculture permit process. Some states produce written guidance to help permit applicants understand the requirements for different mariculture operations and the process and sequence for obtaining them.

Offshore mariculture policy

Regulatory complexity, use conflicts, and (in some cases) water quality issues in nearshore waters have led to greater interest in offshore or open ocean mariculture.

The regulation of offshore mariculture in the United States remains unsettled. At present, there is no federal policy pertaining specifically to the permitting of mariculture in waters under federal jurisdiction, typically 3–200 nautical miles offshore, known as the exclusive economic zone. At a minimum, a Section permit is required from the United States Army Corps of Engineers (USACE), and in some cases, approval from fisheries management councils may be required. In the absence of a settled and transparent regulatory framework, not only is expansion of the existing industry hampered, but potential future growth and research in this area is discouraged (Barr, 1997; Brennan, 1999; National Oceanic and Atmospheric Administration, 1999).

TABLE 1
Synthesis table of legislation and other framework elements

Country	Basic Legislation	Guidelines and Codes of Conduct	International Arrangements	Authorization System	Environment Impact Assessment (EIA)
China	- Fisheries Law and Regulation for the Implementation of the Fisheries Law (1987). - Local laws and regulations	Numerous guidelines have been issued, on various topics, for instance the operation of hatcheries and the use of antibiotics and chemicals in aquaculture.	- Party to the Convention on Biological Diversity (CBD). Signed Biosafety Protocol (BP), but not yet a party. - Party to the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES).	The people´s governments may grant licences to use state-owned water surfaces and tidal flats. After the 2000 amendment, those wishing to use designated areas must apply for an aquaculture permit.	EIA requirements in various environmental laws, but none of which specifically refer to aquaculture. The EIA Law (2002) expands EIA requirements from individual construction projects to government planning for the development of aquaculture, etc.
India	- Indian Fisheries Act (1897); - Environment Act (1986); - Water (Prevention and Control of Pollution) Act (1974); - Wild Life Protection Act (1972).	- Guidelines for Sustainable Development and Management of Brackish Water Aquaculture; - Guidelines for optimizing yield levels and improving the management of shrimp aquaculture.	- Party to the CBD and signed the BP. - Party to the CITES	The Aquaculture Authority is responsible for the authorization system approval. The approval form, given for a period of 3 years, will specify the conditions to the activity.	EIA Notification, in accordance with the Environmental Act, specifies the projects that require an EIA. The list does not include aquaculture, but the Guidelines for Sustainable Development and Management of Brackish Water Aquaculture recommend to carry out a site selection process, which should include proper EIA.
Thailand	- Fisheries Act (1947, amended in 1953 and 1985); - Royal Decree on Administration (1994); - Development Policy; - National Fisheries.	Code of conduct standards for the marine shrimp culture industry; - Good Aquaculture Practice guidelines for hygienic shrimp production with no environmental impacts.	- Party to the CBD but not to the BP. - Party to the CITES	Fisheries Act classifies fisheries into four categories. Anyone that wants to cultivate aquatic animals will need a permission obtained from the Director-General for Fisheries.	Aquaculture is currently not among the range of projects for which an EIA is required.
Indonesia	Fisheries Law n.º 31/2004, which underscores the importance of sustainable use of aquatic resources in the development of fisheries.	Being a member of ASEAN, Indonesia embraces the codes of conduct adopted by the Association, which includes, among others, the Manual of ASEAN Good Shrimp Farm Management Practices Guidelines.	- Party to the CBD and to the BP. - Party to the CITES - Member of Southeast Asian Fisheries Development Center (SEAFDEC)	Fisheries Law requires a specific licence to engage in fisheries business, including aquaculture. Small producers are exempt from such requirement. When required, the EIA is part of the licensing procedure.	Environment Management Act (1997) requires an EIA for any business or activity likely to have a major and significant impact on the environment. The conduct of aquaculture is subject to EIA procedure, as established by Decree of the State Minister of the Environmental Affairs n.º 3/2000.
Bangladesh	- Protection and Conservation of Fish Act (1950) as amended by the Protection and Conservation Ordinance (1982) - Marine Fisheries Ordinance (1983 - Marine Fisheries rules (1983).	There are no guidelines or codes of conduct for aquaculture activities	- Party to the CBD and to the BP. - Party to the CITES	There is no authorization or registration system of aquaculture facilities.	The Environment Protection Act (1995) aims to protect the environment and to control and mitigate environmental pollution. Aquaculture projects are not included.

Country	Basic Legislation	Guidelines and Codes of Conduct	International Arrangements	Authorization System	Environment Impact Assessment (EIA)
Japan	- Fisheries Law (1949, as revised in 1962) - Law to Ensure Sustainable Aquaculture Production (1999).	Basic Guidelines to Ensure Sustainable Aquaculture Production (1999)	- Party to the CBD and to the BP. - Party to the CITES - Member of SEAFDEC	Fisheries Law recognizes three principal categories of fisheries rights, from which the demarcated rights are granted for aquaculture in specific areas.	EIA Law (1997) sets procedures and contains provisions designed to ensure that EIA are conducted properly with respect to large-scale projects that could have a serious impact on the environment. The Law does not specifically refer to aquaculture.
Philippines	- Philippine Environment Code (1988) integrates all relevant laws to these issues. Part of Chapter II of the Code deals with aquaculture.	Code of Practice for Aquaculture, for environmentally-sound design and operation to promote the sustainable development of aquaculture industry	- Party to the CBD and signed the BP, but not yet a party. - Party to the CITES - Member of SEAFDEC	Authorizations are granted by the body that has jurisdiction over the venue of the aquaculture operation.	Fisheries Code requires that activities or projects which will affect the quality of the environment need to prepare a prior detailed Environment Impact Statement. Fishery projects are included in the list of the Environmental Critical Projects.
European Union (EU)	• Water Framework Directive 2000/60/EEC of 23 October; • Marine Strategy Framework Directive 2008/56/CE of 17 June; • Regulation (CE) n.° 710/2009 of 5 August; • Regulation (CE) n.° 535/2008 of 13 June; • Regulation (CE) n.° 708/2007 of 11 June; • Regulation (CE) n.° 506/2008 of 6 June; • Strategy for Sustainable Development of European Aquaculture COM(2002)511, of 19 February 2002 (Communication from the Commission to the Council and the European Parliament)	The Federation of European Aquaculture Producers(FEAP) is open to all national aquaculture associations. FEAP members adopt the 2000 Code of Conduct for European Aquaculture.	EU is a member of several international arrangements, namely: • Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Agreement); • Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) Convention for the Marine Environment Protection and of the Mediterranean Coastal Area (Barcelona Agreement 1995). • North Atlantic Salmon Conservation Organization (NASCO). • Convention on Biological Diversity (CBD); • Convention on the Protection of the Marine Environment of the Baltic Sea Area (HELCOM); • International Baltic Sea Fishery Convention (IBSFC); • North Atlantic Fishery Organization (NAFO); • North East Atlantic Fishery Convention (NEAFC);	No specific legislation	Directive 85/377/EEC of 27 June 1985, modified by Directive 97/11/CE of 3 March 1997.

Country	Basic Legislation	Guidelines and Codes of Conduct	International Arrangements	Authorization System	Environment Impact Assessment (EIA)
USA	Aquaculture is regulated at the federal and state level: • National Aquaculture Act (1980), establishes a National Aquaculture Development Plan and requires federal coordination of aquaculture; • Clean Water Act, the major federal law regulating environmental aspects of marine aquaculture; • Coastal Zone Management Act (1972) requires federal activities to be consistent with State Coastal Management Plans.	The EPA Effluent Limitations Guidelines and New Source Performance Standards for Concentrated Aquatic Animal Production Point Source; Draft Guidance for Aquatic Animal Production Facilities to Assist in Reducing the Discharge of Pollutants, EPA; Code of Conduct for Responsible Aquaculture Development in the United States of America Exclusive Economic Zone (NOOA 2003).	- Party of the CBD - Party to the CITES among others with implications for the regulation of aquaculture	In principle, it is unlawful to conduct aquaculture operations or to culture approved species of aquatic plants and animals unless registered with state authorities. However, this may vary from state to state; The clean Water Act establishes pollution discharge permits and ocean discharge criteria; Open ocean aquaculture requires approval of United States of America Environmental Protection Agency, United States of America Army Corps of Engineers and National Marine Fisheries Service.	The requirement of an environment impact assessment before an aquaculture facility is registered may vary from state to state.
Canada	The aquaculture industry is overseen by a combination of federal, provincial and local authorities.	- National Code System for Responsible Aquaculture. - Another codes of conduct targeted specifically to the aquaculture industry have also been developed at the provincial level.	- Party of the CBD - Party to the CITES, among others with implications for the regulation of aquaculture	Both the federal and provincial governments are authorized to issue licences to engage in and set up an aquaculture facility in Canada.	The Canadian Environmental Act (1992) and its regulations are the legislative basis for the federal practice of environmental assessment. Under the CEAA a marine aquaculture project is subject to an environmental assessment.
Norway	- The Aquaculture Act (2005). - The agreement on the European Economic Area (EEA) imposes several obligations on Norwegian legislation.	There are no guidelines or codes of conduct for aquaculture activities	- Party to the CBD and to the BP. - Party to the CITES	The Aquaculture Act establishes an obligatory licensing system for aquaculture, and provides that the Ministry may, through regulations, prescribe limitations in the number of licences.	Any aquaculture licence may, as a general rule, only be granted if it is "environmentally responsible". The Regulation relative to impact assessment (2005), establishes that an EIA is to be carried out for large aquaculture installations,
Chile	- Fisheries and Aquaculture Law (1989, as amended up to 2006) regulates the conservation of living aquatic resources, capture fisheries, aquaculture and scientific and recreational fisheries.	There are no guidelines or codes of conduct for aquaculture activities	- Party to the CBD but has not yet ratified the BP. - Party to the CITES	The authorization/ concession system to set up aquaculture facilities is regulated by the General Fisheries and Aquaculture Law.	According to the General Law on Environment, the conduct of aquaculture is subject to an environmental impact assessment, with the exception of minor scale aquaculture.
New Zealand	- Resources Management Act (RMA) as amended in 2004. - Freshwater aquaculture activities regulated by the Freshwater Fish Farm Regulations of 1983, under the statutory guidance of the Fisheries Act as amended in 2004.	New Zealand as not adopted a specific code of conduct for fisheries or aquaculture. However, it "fully supports" the FAO Code of Conduct for Responsible Fisheries	- Party of the CBD - Party to the CITES, among others with implications for the regulation of aquaculture	In coastal zones, rules and plans will determine whether resource consents are required to carry out aquaculture related activities Inland fish farming is also subject to an approval, in the form of a resource consent or certificate compliance	The RMA requires that any application for a resource consent must contain an adverse effects assessment, which details the scale and significance of the effects of aquaculture and other activities, upon the environment.

A bill defining federal policy and permit processes for mariculture in the exclusive economic zone, the National Offshore Aquaculture Act, has been introduced several times, most recently in 2007 as H.R. 2010 and S. 1609 in the 111th Congress (NOAA, 2008). The 2007 bill would address the current gaps in United States of America offshore mariculture regulation by:

- authorizing the Secretary of Commerce to issue offshore mariculture permits;
- requiring the Secretary of Commerce to establish environmental requirements for offshore mariculture;
- requiring the Secretary of Commerce to work with other federal agencies to develop and implement a coordinated permitting process for offshore mariculture;
- exempting permitted offshore mariculture from fishing regulations that restrict size, season, and harvest methods;
- authorizing a research and development program for all types of mariculture.

This asymmetry in regulatory instruments and requirements for environmental compliance on a global scale has been an important factor in the delocalisation of aquaculture from Europe and the US to other parts of the world, where there is little concern for the negative externalities that result from unsustainable aquaculture practices.

Main gaps and key elements

Main global carrying capacity and site selection issues and gaps

Table 2 presents a summary of the main issues that are presently considered in carrying capacity and site selection, together with what may constitute future components for assessment.

Feed-based aquaculture taking place in cages (open water) or ponds (inland or fringing) is mainly constrained by holding capacity and wastewater reduction criteria. In Southeast Asia and People's Republic of China there is a greater preoccupation with holding capacity, whereas e.g. in the European and the United States of America legislation drives a greater emphasis on negative externalities.

TABLE 2
Novel management approaches (adapted from Ferrreira et al., 2010)

Topic	Now	Tomorrow
Feed-based (cage, pond)	Site selection based on holding capacity (cages), wastewater minimization (ponds)	Integrated model systems, risks, welfare, disease. Holistic indicators LCA: inefficiencies and eco-labelling Mechanistic and statistical models Data assimilation models
Shellfish farming	Large areas Focus on production and social carrying capacity NIMBY[3], NIMTO[4]	Economic sustainability, ecology and economics Coupled GIS expert systems including xenobiotics HAB, etc Model uncertainties in yield Early warning
Integrated Multi-Trophic Aquaculture	Optimize production Reduce negative externalities	Integrated Coastal Zone Management. Simulate species combinations Full economic assessment. Combine GIS, remote sensing, and modelling
Ecosystem Approach to Aquaculture (EAA)	Development of concept and practical implementation	Ecological aquaculture, balancing multisectorial requirements, ecosystem equilibrium, and social equity. Many of the tools that will be used in IMTA are applicable, much more will emerge on social components where "hard" models are a challenge. Achievement of more equitable global balance.

[3] Not in my backyard
[4] Not in my term in office

More intensive aquaculture and volume of production tends to occur in nations that are currently developing regulation, and where there is weak enforcement, and /or low consideration to environmental effects. On the other hand in some of these countries food security and social needs are higher ranked than environment (Figure 1) particularly in consideration to high population density in coastal zones. This could be the case in some Asian countries such as it is shown in Figure 3 that illustrates aquaculture production normalised to coastline length and area.

However, in some cases such in the People's Republic of China the intensity of cultivation in coastal bays, may often constitute a positive environmental impact (see below).

As an example of potential aquaculture pressure on coastal ecosystems, Figure 4 shows a mass balance for shrimp cultivation, simulated by means of the POND model (Ferreira *et al.*, 2010) that estimates an environmental discharge of over 60 kg (i.e. total output) of nitrogen (mostly dissolved, but also as algae), roughly 20 population-equivalents per year for the 110 day cultivation cycle. This corresponds to an abatement cost of about US$800 (Lindahl *et al.*, 2005). Frequently these waste costs are not internalized, but would need to be determined in the scope of EAA, and are increasingly required for product certification in western markets. Currently, pond production in the United States already requires a National Pollutant Discharge Elimination System (NPDES) permit (Boyd, 2009). In practice this means that large agri-industrial companies from developed nations

FIGURE 3
Intensity of aquaculture per unit coastline and per total (marine + land) area

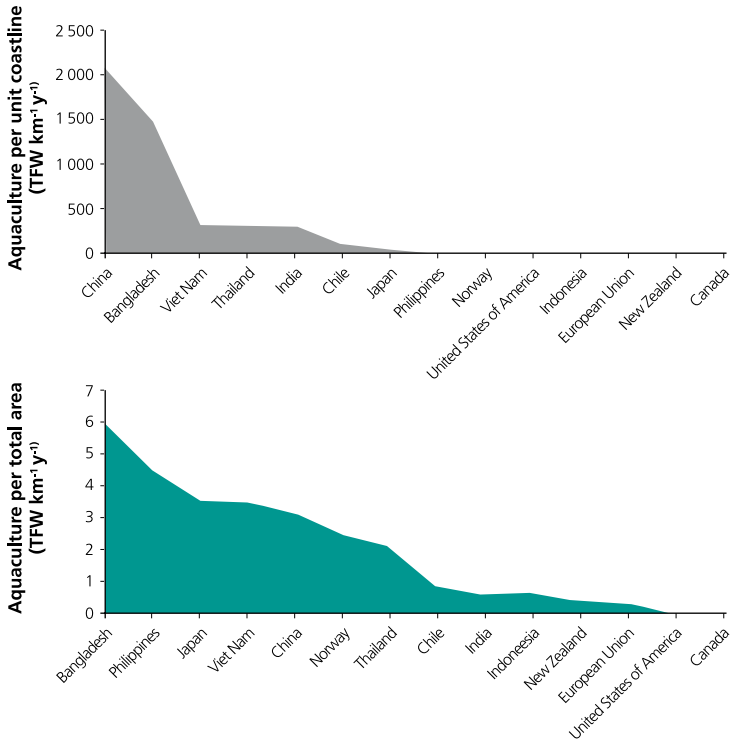
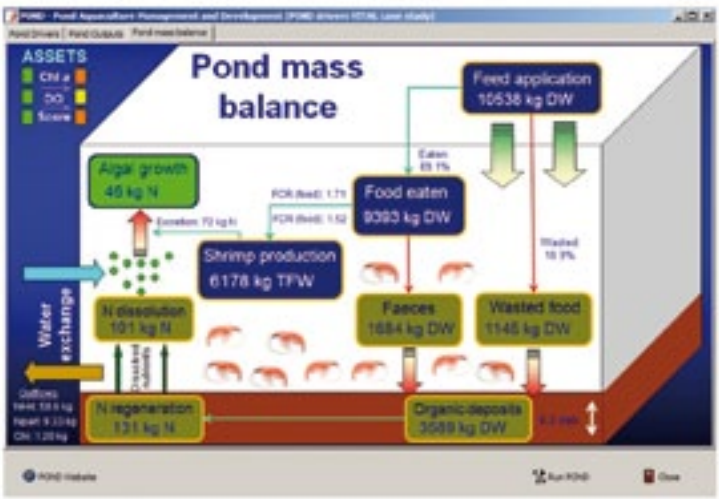
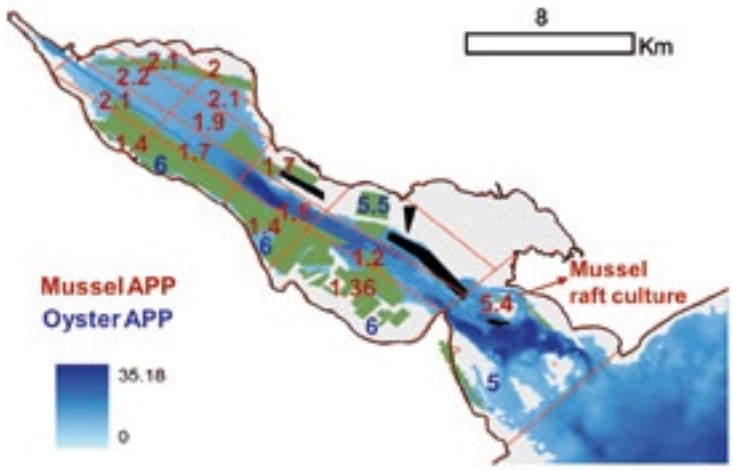


FIGURE 4
POND mass balance output for a 1 ha farm, including Feed Conversion Ratio (FCR), diagenesis, primary production, effluent discharge, and ASSETS eutrophication rating



Source: Ferreira *et al.* (2010).

FIGURE 5
Average physical product (APP = output/input) for bottom culture of blue mussel *Mytilus edulis* (in red), and *Pacific oyster* (in blue) in Carlingford Lough, Ireland, determined in the SMILE project with the EcoWin2000 ecological model



Source: Ferreira *et al*. (2008).

price-leverage the lack of environmental regulation and/or implementation in the developing world.

Organically extractive aquaculture takes place on a very different spatial scale, due to the nature of the food supply, and results in the occupation of relatively large areas, often including shorefront leases. The issues that have emerged with respect to carrying capacity have been largely (i) production-related, such as the reduced growth and harvest size of the Pacific oyster *Crassostrea gigas* in the Marennes-Oléron area of the French Republic in the mid-1990's, largely due to overstocking (Raillard and Ménesguen, 1994), or (ii) social concerns in developed nations on the use of waterfront areas (e.g. the geoduck industry in Puget Sound, Cheney *et al*., 2010), landscape values etc.

In the few system-scale carrying capacity studies that have taken place (e.g. Ferreira *et al.*, 2008b) it is clear that even from a production perspective (Figure 5) there appears to be room for improvement in terms of site selection. With respect to environmental issues, there is a debate on the impacts due to biodeposits and consequent sediment organic enrichment.

Appropriately dimensioned shellfish culture seems to have little effect on the benthos (e.g. Fabi, Manoukian and Spagnolo, 2009), even when large areas are occupied (Zhang *et al.*, 2009). On the other hand, the positive externalities of bioextraction for top-down control of eutrophication symptoms have been documented in many parts of the world (e.g. Xiao *et al.*, 2007), and it is clear that the existence of significant shellfish aquaculture e.g. in the People's Republic of China has been instrumental in controlling coastal eutrophication, probably on a national scale (Sorgeloos, 2010), as industrial and urban pressure on coastal zones has mounted in the last decades.

An additional issue for shellfish cultivation is the interaction with the development, frequency, and duration of harmful algal blooms (HAB). This is presently in debate, given both the lack of clarity in many cases as to the drivers and processes that trigger HAB, and the effects on human health. There are significant areas of the coastal ocean where carrying capacity is limited by such HAB events, often unrelated to human-originated nutrient loading.

Integrated multi-trophic aquaculture (IMTA) has long been practiced in Asia, and is a mainstay e.g. of aquaculture in the People's Republic of China. Presently the interest in co-cultivation across trophic levels is growing in the EU and the United States of America. The focus once again is more on optimal production in developing countries, whereas in developed countries the emphasis is on reduction of emissions. There is a clear link between the two since for instance hypoxic pond water is not only an external environmental liability but also an internal factor of increased mortality.

Two important issues that are not often considered and constitute potential liabilities of IMTA are:

[5] The higher value for raft culture of mussels is due to much better survival, particularly of seed

(i) The potential for disease vectors to "jump" across trophic levels, thereby impacting the whole co-cultivation system. Conversely, it has been pointed out (Chopin *et al.*, 2010) that blue mussels in IMTA with Atlantic salmon may be instrumental through filtration in reducing the incidence of salmon lice in finfish cages; and

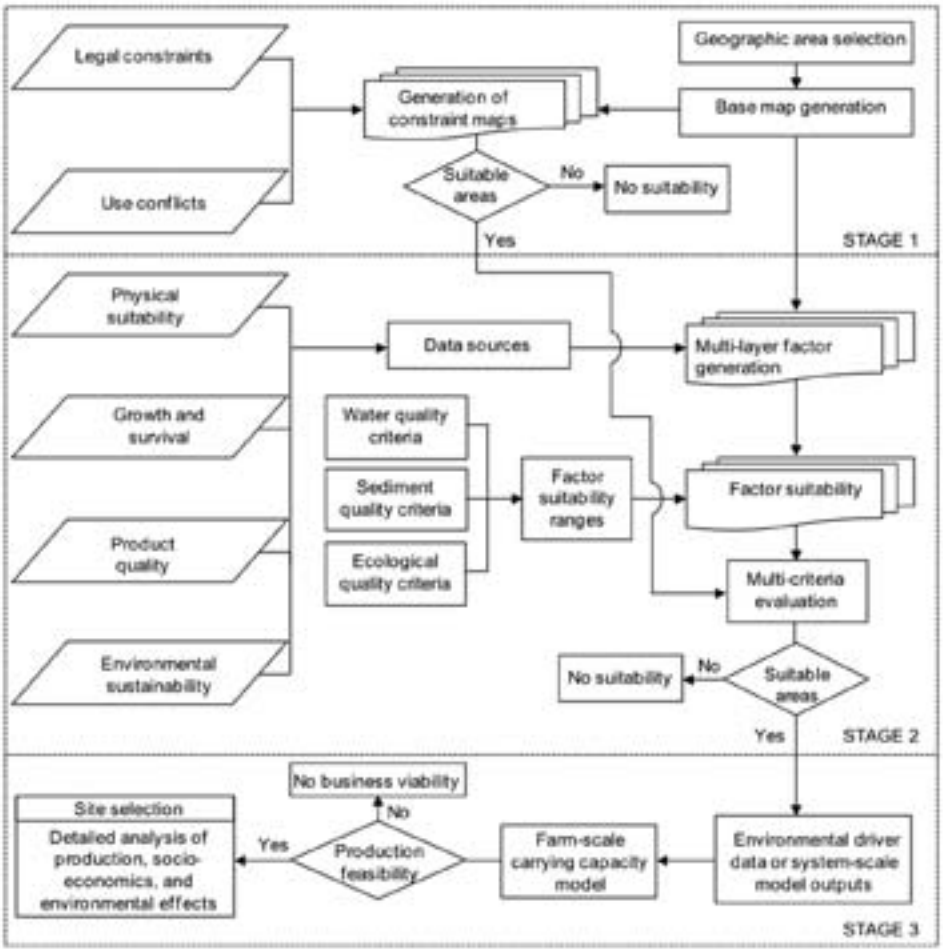
(ii) Any fluctuation in yield for one component of an IMTA system can potentially have serious consequences with respect to the environmental balance of the whole. This can occur through a disease outbreak in one or more trophic levels, but also if parts of the culture become economically unattractive, leading to an equilibrium shift. For example, an offshore area of 5 km^2 along the 30m bathymetric line is currently being developed in southern Portugal, planned for 60 leases, of which 70 percent for finfish and 30 percent for shellfish; these leases are independently contracted, and if market shifts determine changes to production, this may lead to unexpected environmental effects.

Use of surrogates and models for decision support

Recommended selection criteria and tools

Decision-support for future expansion and optimization of aquaculture operations can make use of a wide range of indicators, indices, and models, drawing from a considerable volume of work (see e.g. www.ecasatoolbox.org.uk/).

FIGURE 6
General top down approach for carrying capacity assessment combining GIS and dynamic modelling



Source: adapted from Silva *et al.* (2011).

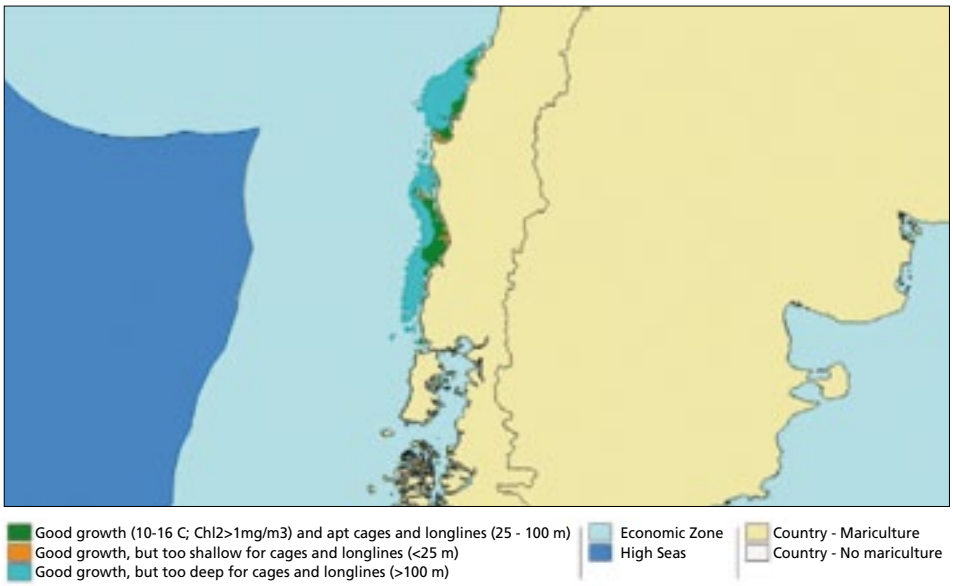
While carrying capacity has a multipolar focus, and should be assessed accordingly, site selection is herein considered to be essentially spatial in nature.

By definition, the general suitability of an area (at the scale of an embayment, offshore coastal zone, or land region) is an issue of carrying capacity rather than site selection, and should be the object of an initial assessment that determines (i) overall suitability; and (ii) limits to cultivation. The latter may include protection of biodiversity (Sequeira *et al.*, 2008), environmental effects (Ferreira *et al.*, 2008a; Ferreira *et al.*, 2008b), and identification of spatial usage conflicts (Ferreira *et al.*, 2010).

Within this wider context, there are clear distinctions between open water and land-based areas, the former being the object of marine spatial planning exercises presently occurring in various parts of the world, whereas the latter are already heavily regulated, particularly in developed nations. Nevertheless, the planning process should flow from a broad assessment of carrying capacity to detailed site selection, focused on a narrower spatial scale and supporting specific licensing procedures. A general approach, adapted from Silva *et al.* (2011) is presented in Figure 6. At all stages of the process virtual technologies are valuable for decision support, providing a means to evaluate tradeoffs among social, environmental, and economic components of sustainability. The type of approach shown in Figure 6 draws heavily on Geographic Information Systems (GIS), a valuable modelling tool both in prospective studies and in assimilating and presenting results of other kinds of models.

GIS is limited in its capacity to represent time-varying phenomena, and these are usually of importance, but it can be combined for instance with remote sensing data (Figure 9) to provide a spatial image of site suitability. This type of approach is applicable also for land-based aquaculture, drawing on spatial information on water resources, land cover, and other thematic data. The extension of GIS approaches such as those reported by Corner *et al.* (2006) and Radiarta, Saitoh and Miyazono (2008) to include dynamic growth models is a promising area of research (Kapetsky, Aguilar-Manjarrez and Jenness, 2012; Silva *et al.*, submitted), since it allows decision-makers to examine the temporal variation of local production and environmental effects within a wider

FIGURE 7
GIS combined with satellite remote sensing: identification of potential areas for IMTA of salmon and mussels in Chile, based on remotely sensed sea surface temperature and chlorophyll data



Source: Kapetsky *et al*. (2010).

spatial context. GIS is relatively inexpensive by comparison to dynamic models, and a combination of both tools optimizes resource use with respect to potential benefits.

For off-the-coast or offshore areas, the review by Ferreira *et al.* (2010) provides three different illustrations (Table 3) of the application of virtual technologies for carrying capacity and site selection. These range from (i) simple ecological models (Nº1) focusing on primary production and mussel growth (Filgueira and Grant, 2009); to (ii) integrated catchment and bay-scale modelling (Nº2) of multiple finfish and shellfish species, including some economic aspects (Nobre *et al.*, 2010); and (iii) management systems (Nº3) combining GIS with dynamic models for circulation, and seeking to incorporate novel aspects such as simulations of salmon lice propagation (Ervik *et al.*, 2008). These approaches are not directly transferrable to land-based culture, although some of their components, such as growth models for cultivated species, or models of biogeochemical cycles, may be re-used.

TABLE 3
Case study examples for carrying capacity and site selection

	Case Study Nº 1 Prince Edward Island	Case Study Nº 2 SPEAR	Case Study Nº 3 AkvaVis
Main management issue(s)	Ecological carrying capacity	Carrying capacity for Integrated Multi-Trophic Aquaculture	GIS for site selection, carrying capacity, and management monitoring in aquaculture
Stakeholders	Water managers, aquaculturists	Water managers	Water managers, aquaculturists
Location	Prince Edward Island, Canada	Sanggou Bay, China	Hardangerfjord, Norway
Scale	Bay	Bay	Bay, local
Cultured species	Blue mussel	Finfish, shellfish and seaweeds	Finfish and shellfish
Data and information types	Field, experimental	Field, experimental, GIS, remote sensing	Field, GIS, desk-based
Tools and model types	GIS, dynamic system-scale models	Dynamic system-scale models, catchment models etc (multilayered)	GIS, socioeconomic instruments, models
Platform	Console	console/Web	Web
Decision-support	Licensing, production, and environmental effects	Licensing, species combinations, production, and environmental effects	Management monitoring, site selection, and licensing

One of the main challenges for production and environmental sustainability in pond culture is optimization, i.e. EAA in this context means optimal yields without imposing the externality costs on the environment. Models can provide valuable information on different options, as illustrated in Table 4.for monoculture of the white shrimp *Litopenaeus vannamei* when compared to co-cultivation with the Pacific oyster *Crassostrea gigas*.

The two simulations illustrate the value of adding filter feeders to the shrimp ponds. In this example for a large farm, typical of some of the industrial scale shrimp production operations, co-cultivation of oysters adds about 25 percent to the top line (income), but doubles the bottom line (profit) due to the low costs of shellfish production. The filter feeders also account for a 60 percent reduction in the chlorophyll concentration in the pond effluent, although oyster excretion increases the output of ammonia.

The Assessment of Estuarine Trophic Status (ASSETS) grade (Bricker, Ferreira and Simas, 2003; Ferreira, Hawkins and Bricker, 2007) changes from Moderate to Good status due to the removal of phytoplankton by the oysters. Screening models such as ASSETS are valuable from a management point of view because they combine indicators into indices,

providing an aggregated image of the environmental status of different management options. Figure 10 illustrates another example of optimization, for mussel culture in Killary Harbour, Ireland, comparing two models at differing scales (Nunes *et al.*, 2011).

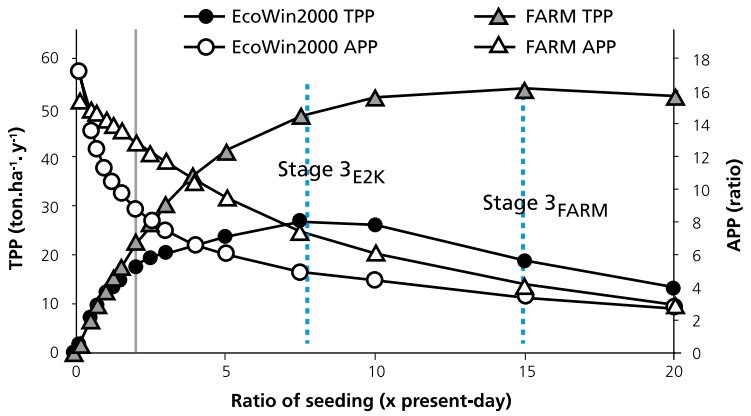
TABLE 4
Application of the POND model to simulate production and environmental effects of shrimp cultivation in monoculture and IMTA with oysters. Cultivation layout: 106 m^2, 90 day cultivation period, water renewal of 15 X 103 m^3/day (3 percent of pond volume) throughout the culture cycle.

Variable	Shrimp monoculture	IMTA of shrimp and oysters	
Model inputs			
Seeding density (kg TFW[3])	35,000	35 000	14 000
Seed weight (g)	0.7	0.7	10
Harvest weight (g)	16	16	30
Natural mortality (percent culture/cycle)	30	30	5
Model outputs			
Production			
Total Physical Product (TPP) (kg TFW)	619 226	619 226	83 320
Average Physical Product (APP)	17.7	17.7	5.95
Feed application (kg DW)	788 200	788 200	-
Feed Conversion Ratio	1.27	1.27	-
Environmental impact in the ponds			
Faeces (kg DW)	129 400	129 400	1 298
Excretion (kg N)	5,400	5 400	258
Organic deposits (kg DW)	250,400		220 200
Nitrogen regeneration in sediment (kg N)	8,500		11 500
Nitrogen dissolution from sediment (kg N)	6,200		8 300
Net primary production (kg N)	2,400		1 200
Nitrogen removal (kg N/year)			
Phytoplankton (kg N/year)	-		-1 349
Detritus (kg N/year)	-		-7
Faeces (kg N/year)	6710		273
Mortality (kg N/year)	2560		7
Mass balance	-		-818
Population equivalents (PEQ/year)	-		248
ASSETS chlorophyll score	in ■ → ■ out	in ■ → ■ out	
ASSETS dissolved oxygen score	in ■ → ■ out	in ■ → ■ out	
ASSETS overall score	in ■ → ■ out	in ■ → ■ out	
Environmental externalities			
Outflow of NH4+ (kg N)	4 410		6 840
Outflow of particulate nitrogen (kg N)	510		230
Outflow of chlorophyll (kg chl)	70		30
Profit and loss			
Aquaculture products (US$)	3 096 132	3 096 132	833 196
Total income (US$)	**3 096 132**	**3 096 132**	**833 196**
Feed (US$)	788 164		788 164
Seed (US$)	1 000 000	1 000 000	7 000
Energy (US$)	69 363		69 804
Total expenditure (US$)	**1 857 527**	**2 257 968**	**7 000**
Income-Expenditure (US$)	**1 238 605**	**1 238 164**	**826 196**
Farm profit (US$)	**1 238 605**	**2 064 360**	

EcoWin2000 (E2K) is an ecological model applied at the system scale, whereas FARM simulates production and environmental carrying capacity at the local scale. Any model of this type, as well the type of pond-scale model described previously, can be used to perform a marginal analysis (Ferreira, Hawkins and Bricker, 2007) to determine stocking densities that lead to optimal profitability.

[6] TFW: total fresh weight (with shell)

FIGURE 8
Impacts of different mussel stocking densities on Total Physical Product (TPP) and Average Physical Product (APP, the ratio between seeded and harvested biomass) as simulated by EcoWin2000 (system scale, per unit of cultivated area) and FARM (single farm) for Killary Harbour, Ireland



Source: Nunes (2011).

This is extremely useful for licensing purposes, since farms often maximise income rather than profit (i.e. aim for the highest TPP). It can be seen that for a coastal or semi-enclosed system there appear to be significant differences between the results for the system-scale model, where the dotted line indicating highest TPP (which exceeds the seeding density of maximum profit) occurs at a density 7-8 times greater than the current situation. FARM however, which deals only with the local scale, determines the end of Stage 2, i.e. highest TPP, as around X15 density. This reflects the fact that (i) the ecosystem model data reports what is actually harvested, since E2K runs multiple production cycles, typically for periods of 10-20 years, whereas FARM reports what is harvestable over one cycle; and (ii) FARM does not account for interactions among farms, whereas E2K considers all the farms in a particular waterbody. Figure 5 illustrates how E2K model boxes are distributed in a system (Carlingford Lough, Ireland), and how this kind of dynamic model is combined with GIS to provide the bathymetry, location of aquaculture leases, and other features.

In fed aquaculture the law of diminishing returns does not apply directly with respect to the food supply, at least on a local scale, given that there is no depletion of natural food resources as occurs for instance in bivalve shellfish culture. However, the increase in stocking density has other consequences, for instance in the increased competition for space and for other factors such as dissolved oxygen. The TPP and APP curves (Figure 9) are obtained by progressively increasing the stocking density of *Litopenaeus vannamei* in ponds, using the POND model. At higher densities growth is constrained by the reduction in dissolved oxygen, due to increased respiration and diagenesis of faeces and uneaten food. The first derivative of the production curve is the marginal physical product i.e.:

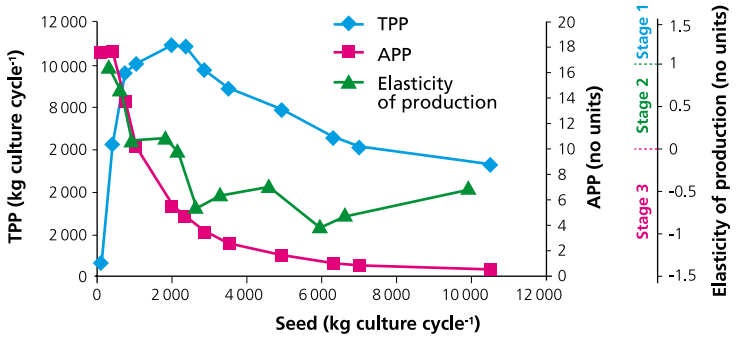
$$MPP = \frac{d(TPP)}{dS} \qquad \text{(Eq. 2)}$$

where: S = stocking density of seed and the elasticity of production E_p is defined (Eq. 3) as the percentage change in output (Y) with respect to percentage change in input (X):

$$E_p = \frac{\frac{\Delta Y}{Y}}{\frac{\Delta X}{X}} = \frac{\Delta Y}{\Delta X} * \frac{X}{Y} = \frac{MPP}{APP} \qquad \text{(Eq. 3)}$$

The model outputs can be used to calculate elasticity of production for a particular culture situation (Figure 11), and show that production becomes progressively more inelastic as the stocking density increases, i.e. relative changes in seed input have progressively smaller effects on production, until they lead to an effective decrease in output.

FIGURE 9
Production function with oxygen limitation for fed aquaculture of penaeid shrimp, simulated using the POND model



Source: Ferreira *et al.* (in press).

The issue of disease is another important area for development of carrying capacity models. The potential disease interactions of IMTA (both positive and negative), have already been discussed, but there is very little work on combining production and animal welfare models, although there is substantial empirical evidence on the association of disease with water quality degradation, overstocking, relaying, and inappropriate feeds. The risks of disease outbreaks can to some extent be spatially mapped, and although the models are stochastic, scenarios can be developed that may allow for proactive management. An example of this type of risk is the exponential growth of *Pangasius* culture in the Mekong delta, driven by European and US imports, and which if uncontrolled will not only have significant effects on product quality and market perception, but will also potentially lead to a collapse of the local industry in the Socialist Republic of Viet Nam, with serious social consequences.

The level at which carrying capacity and site selection models may be applied depends on various factors. In the first instance it is driven by legislation, best practice agreements, and by public pressure, usually routed through NGO's or citizens' groups. Secondly, some models are harder to apply than others, in terms of data requirements, cost, and technical expertize. Thirdly, some areas are less amenable to modelling, but equally important in decision-making. Foremost is the social component, which as previously stated is a key limit to aquaculture expansion in Europe, the US, and Canada, and where decisions are largely based on belief. A better integration of models for the natural and social systems is an important research area for EAA. Some steps (e.g. Nobre *et al.*, 2009) have been taken in that direction, but it is critical for economic models to provide feedback to ecological models, to potentially incorporate aspects such as employment or market dynamics.

Integration with regulation and governance

Regulation and governance standards in aquaculture vary widely throughout the world, which to an extent reflects the prevailing social conditions and priorities. Other texts that form part of this volume address these aspects in more detail; we limit ourselves herein to highlighting the role that simulation models of various types can play in supporting those societal choices.

Current and future issues and bottlenecks

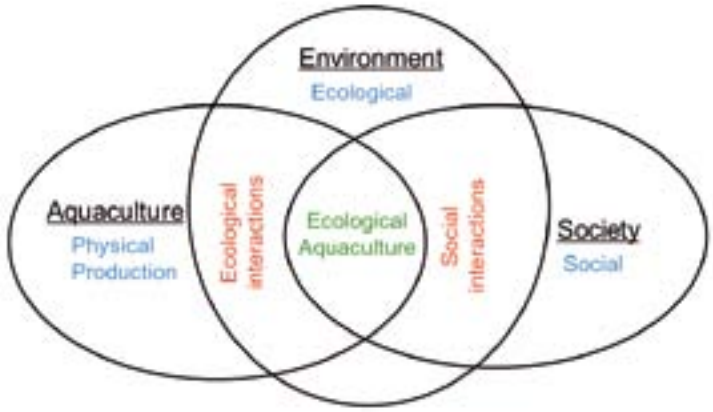
The application of the EAA on a worldwide scale requires the harmonization of (i) environmental; (ii) social; and (iii) multi-sectorial planning objectives (Soto, Aguilar-Manjarrez and Hishamunda, 2008). These three principles and their relative weights are by definition different across world regions, making it socially and politically impractical to define a standard for uniform compliance with respect to limits and thresholds.

Rather, it is important to establish appropriate approaches, such that within a particular world region a gradient can be defined in relative terms, assessing EAA in terms of the principles stated above. The three principles of EAA can be mapped onto the four pillars of carrying capacity, and illustrated as the overlap of these (Figure 10).

The importance (size) of each of the circles represented will vary regionally, and will develop through time based on the natural feedbacks society provides.

The practical use of models for addressing some of the aspects represented in Figure 12 depends on various constraints (Table 5).

FIGURE 10
Harmonisation of the four pillars (in blue) of carrying capacity to arrive at an ecosystem approach to aquaculture (in green)



The regulatory level provides the initial impetus for an EAA approach; thereafter two other hurdles must be overcome. The first is the scientific and technological barrier to entry with respect to model application which includes financial access, data-poor environments, and lack of expertize. The second has already been mentioned, i.e. the social aspects that are challenging to model but form a significant part of the EAA.

TABLE 5
Application of carrying capacity and site selection models

Regulatory level	
Legislation (internal, international, or external, such as import regulations)	
Best practice agreements (certification etc)	*Drivers*
Public pressure (NGOs, citizens' groups…)	
Scientific and technical level	
Difficulty in model implementation	*Feasibility*
Data requirements, cost, expertize	
Some areas less amenable to modelling	
Social component	*Inclusion*
Belief-driven, but equally important	

Some of these can be addressed using GIS approaches that consider multi-sectorial planning (Figure 12), but others are belief-driven and must be included through a participative approach.

A 50 percent annual increase in aquatic production is required by 2050 to accommodate the needs of the global human population. This increase of 30 MMT (Swaminathan, 2010) translates to a net production area of 30,000 km^2, for an annual yield of 1 kg/m^2. The gross area would be equivalent to 100-150 X 10^3 km^2, taking into account facilities and processing infrastructure; this is roughly twice the area currently under cultivation in the People's Republic of China. As discussed previously, this expansion will not take place in Europe, the United States of America, or Canada, but in developing nations. In many Asian countries, the proportion of available land occupied by aquaculture is nearing capacity, together with a good deal of the coastline. More efficient cultivation methods will increase yields of existing farms, but greater environmental awareness will tend to reduce production.

Africa is one of the world regions with the lowest aquaculture production, and simultaneously suffers from massive food security problems. It appears therefore to have the potential for development of aquaculture as a means to alleviate poverty

FIGURE 11
Cage culture of yellow croaker in Sandu Bay, China (260 000 cages)

Source: Image @2012 Digital Globe

and increase the food supply to local populations. However due to restrictions in access to water, land-based aquaculture would need to be confined to areas with adequate rainfall, whereas other areas, particularly in the Indian Ocean, are suitable for offshore aquaculture. The challenge is to ensure this development follows an ecosystem approach, rather than one that neglects the protection of natural and human capital.

Recommendations

It is clear that virtual technologies, whether they be GIS, satellite remote sensing, dynamic models, or others, can play a huge role in addressing the physical, production, and environmental pillars of site selection and carrying capacity. From the environmental perspective, which is the focus of this review, the examples provided illustrate the value of such tools. However, models need to be more production- and management-oriented, and adapt to local realities and conditions. This requires a more effective linkage between industry and research to create objective-led demand for virtual technology-driven RTD, and a clear view of the business models that might support it.

In parallel, research into improved models for social aspects, and for the connection to environmental aspects, needs a much greater effort. This will establish a more quantitative basis for discussion and for decision-making, enabling a better understanding of trade-offs.

Distributed computing, and in particular the use of smartphone technology to combine location data, Web communication, and computational applications, is a paradigm shift at least as important as the appearance of the world wide web in the 1990's. It has great potential in bridging the information gap in many thematic areas, and should certainly be used to improve the understanding of aquaculture-environment interactions, simulate local conditions in real time, and interpret the outputs of sensors.

Aquaculture is particularly important to developing countries, where it is not only critical in supporting healthy food provision but is also an important source of income for local communities. These nations often have a comparative advantage, i.e. it makes sense economically for resources to be used in aquaculture production, because it can be done at a lower cost than in developed countries. It is important however that production in developing countries should not translate into negative environmental externalities

considered unacceptable in the developed world. The modelling approaches discussed in this review and in Ferreira *et al.* (2010), together with currently emerging work, promise exciting times ahead for the role that virtual technologies will increasingly play in implementing an ecosystem approach to aquaculture.

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TABLE 6
Relevant legislation – Asia

Country	Basic Legislation	Guidelines and Codes of Conduct	International Arrangements	Authorization System	Environment Impact Assessment (EIA)
China	The Fisheries Law (1986, amended in 2000) seeks to enhance the production, development and reasonable utilization of fisheries resources. It requires the state to adopt a policy that calls for simultaneous development of aquaculture, fishing and processing, with special emphasis on aquaculture. The Law is implemented by the Regulation for the Implementation of the Fisheries Law (1987). The Bureau of Fisheries, falling under the Ministry of Agriculture, is the main administrative body governing aquaculture sector. Over last decades, many local laws and regulations with relevance for aquaculture have been adopted.	Numerous guidelines have been issued, at both the national and the provincial level, on various topics, for instance the operation of hatcheries and the use of antibiotics and chemicals in aquaculture.	China is a party to the Convention on Biological Diversity (CBD). It has signed the Biosafety Protocol, but is not yet a party to the protocol. China is also a party to the Convention on international Trade in Endangered Species of Wild Fauna and Flora (CITES).	According to the Fisheries Law and its implementing Regulation, the people´s governments may grant licences to use state-owned water surfaces and tidal flats to develop aquaculture. After the 2000 amendment, the State draws plans for the use of water surface areas and defines those for aquaculture purpose. Units or individuals wishing to use those designated areas must apply for an aquaculture permit.	Provisions on EIA requirements can be found in various environmental laws, none of which, however, specifically refer to aquaculture. The Law on the Prevention and Control of Water Pollution, aims to prevent and control pollution of rivers, lakes, reservoirs and other surface waterbodies and groundwater. According to the law, the environmental impact statement of construction projects, including large-scale aquaculture projects, should contain an assessment regarding the water pollution hazards, including the impact on the ecosystem and a description of measures for prevention and control. The same applies to coastal construction projects. The EIA Law (2002) which has taken effect on September 2003, expands EIA requirements from individual construction projects to government planning for the development of, inter alia, aquaculture, water conservation and natural resources.

Country	Basic Legislation	Guidelines and Codes of Conduct	International Arrangements	Authorization System	Environment Impact Assessment (EIA)
India	At central level, several key laws may be relevant to aquaculture. They include the Indian Fisheries Act (1897) which penalizes the killing of fish by poisoning water and by using explosives, and the Environment Act (1986) containing provisions for all environment related issues. They also include the Water (Prevention and Control of Pollution) Act (1974) and the Wild Life Protection Act (1972) All this legislation must be read in conjunction with one another to gain a full picture of rules that are applicable to aquaculture.	The Ministry of Agriculture issued Guidelines for Sustainable Development and Management of Brackish Water Aquaculture in order to assist in formulating appropriate shrimp farming management practices and adopting measures for mitigating the environment impact for management of shrimp pond wastes and utilization of resources in a judicious manner. The guidelines also recognize the importance of wastewater treatment and prescribe standards for the treatment of wastewater discharged from aquaculture systems, hatcheries, feed mills and processing plants. Recently the Aquaculture Authority formulated guidelines with the objective of optimizing yield levels and improving the management of shrimp aquaculture in traditional systems, to ensure log-term sustainability of the farming practices and environmental security	India is a party to the Convention on Biological Diversity (CBD) and has signed the Biosafety Protocol. India is also a party to the Convention on international Trade in Endangered Species of Wild Fauna and Flora (CITES)	The Aquaculture Authority is responsible for the authorization system approval. The application forms needs to specify several issues, namely the identification of possible negative effects that the activity may cause to the environment. The approval form, given for a period of 3 years, will specify the conditions to the activity. Also an aquaculture farmer will be required to obtain an authorization form from the Pollution Control Board to set up a treatment and disposal system that is likely to discharge sewage or trade effluent into waters or onto the land.	The Environmental Impact Assessment Notification (1994), in accordance with the Environmental Act species the projects that require an EIA. The list does not include aquaculture. However, the Guidelines for Sustainable Development and Management of Brackish Water Aquaculture (1995) recommend to carry out a site selection process, which should include proper EIA. They state that all aquaculture units above 40 hectares should be subject to an EIA. Shrimp culture units above 40 ha should incorporate an environmental Monitoring Plan and an Environmental Management Plan, covering the following potential impacts: local watercourses, groundwater, agriculture, soil and salinisation, waste water treatment and green belt development. Smaller farms, between 10 and 40 ha, must also provide information on these items.

Country	Basic Legislation	Guidelines and Codes of Conduct	International Arrangements	Authorization System	Environment Impact Assessment (EIA)
Thailand	The Fisheries Act (1947, amended in 1953 and 1985) is the principal legislative instrument, complemented by the Royal Decree on Administration (1994), which provides the Department of Fisheries with the authority to apply, implement and enforce the Fisheries Act. The overall strategy for country ´s fisheries management is stipulated in the National Fisheries Development Policy, which strategy includes the strengthening of aquaculture techniques and management, promoting cost-effective and environmentally-friend aquaculture.	Code of conduct standards have been developed for the marine shrimp culture industry, in order to achieve international quality standards and to manage the environment for the whole production line. In addition, Good Aquaculture Practice guidelines have been developed for hygienic shrimp production. To produce good quality and safe shrimps for consumers, shrimp farms may be standardized, clean, sanitary, and generate no environmental impacts.	Thailand is a party to the Convention on Biological Diversity (CBD) but not to the Biosafety Protocol. Thailand is also a party to the Convention on international Trade in Endangered Species of Wild Fauna and Flora (CITES)	The Fisheries Act classifies fisheries into four categories, i.e. preservation, leasable, reserved and public fisheries. In any case, anyone that wants to cultivate aquatic animals will need a permission obtained from the Director-General for Fisheries and shell comply with the conditions imposed.	Aquaculture is currently not among the range of projects for which an EIA is required.

Country	Basic Legislation	Guidelines and Codes of Conduct	International Arrangements	Authorization System	Environment Impact Assessment (EIA)
Indonesia	At national level fisheries and aquaculture are regulated by Fisheries Law n.º 31/2004, which underscores the importance of sustainable use of aquatic resources in the development of fisheries. This Law defines fisheries as all the activities related to the cultivation and utilization of fish resources, which includes both aquaculture and capture fisheries.	Being a member of ASEAN, Indonesia embraces the codes of conduct adopted by the Association, which includes, among others, the Manual of ASEAN Good Shrimp Farm Management Practices Guidelines.	Indonesia is a party to the Convention on Biological Diversity (CBD) and to the Biosafety Protocol. India is also a party to the Convention on international Trade in Endangered Species of Wild Fauna and Flora (CITES). AS part of the Southeast Asian Fisheries Development Center (SEAFDEC) Indonesia participates in the Departmental Programmes on Aquaculture and also in the SEAFDEC-ASEAN Programmes, which include the promotion of mangrove-friendly aquaculture and the regionalization of the Code of Conduct for Responsible Fisheries.	The Fisheries Law requires a specific licence to engage in fisheries business, including aquaculture.Small producers are exempt from such requirement.	Pursuant to Environment Management Act (1997) an EIA is required to engage in any business or activity likely to have a major and significant impact on the environment. In this regard, the conduct of aquaculture is subject to EIA procedure, as established by Decree of the State Minister of the Environmental Affairs n.º 3/2000. When required, the EIA is part of the licensing procedure for the conduct of the concerned activity.
Bangladesh	The basic act regulating inland fisheries is the Protection and Conservation of Fish Act (1950) as amended by the protection and Conservation Ordinance (1982) The Marine Fisheries Ordinance (1983) as implemented by the marine Fisheries rules (1983) is the basic act regulating marine fisheries. Although the basic fisheries legislation does not have separate sections on aquaculture, some of its provisions are relevant to the subject. Other legislation relevant to aquaculture includes the Tanks Improvement Act (1939), which provides for the improvement of tanks for irrigation and aquaculture purposes	There are no guidelines or codes of conduct for aquaculture activities	Bangladesh is a party to the Convention on Biological Diversity (CBD) and the Biosafety Protocol. Bangladesh is also a party to the Convention on international Trade in Endangered Species of Wild Fauna and Flora (CITES)	There is no authorization or registration system of aquaculture facilities.	The Environment Protection Act (1995) aims to protect the environment and to control and mitigate environmental pollution. Aquaculture projects are not included in the Schedule 1 of the rules, which provides the category classification of most common industries. The Environment Protection Act sets water quality standards for inland surface waters used for fisheries and aquaculture

Country	Basic Legislation	Guidelines and Codes of Conduct	International Arrangements	Authorization System	Environment Impact Assessment (EIA)
Japan	The principle law that regulates fishery activities is the Fisheries Law (1949, as revised in 1962), which deals with several kinds of fishing rights and licences for individuals and groups of persons. Also the Law to Ensure Sustainable Aquaculture Production (1999), seeks to prevent the self induced environmental deterioration around fish farms.	Pursuant to the Law to ensure Sustainable Aquaculture Products, the Ministry of Agriculture, Forestry and Fisheries (MAFF) issued Basic Guidelines to Ensure Sustainable Aquaculture Production (1999)	Japan is a party to the Convention on Biological Diversity (CBD) and to the Biosafety Protocol. Japan is also a party to the Convention on international Trade in Endangered Species of Wild Fauna and Flora (CITES) and a member of Southeast Asian Fisheries Development Center (SEAFDEC)	The Fisheries Law recognizes three principal categories of fisheries rights, from which the demarcated rights are granted for aquaculture in specific areas and are usually valid for five years.	The EIA Law (1997) sets procedures and contains provisions designed to ensure that EIA are conducted properly with respect to large-scale projects that could have a serious impact on the environment and prescribes measures to reflect the results of EIA in implementing such projects. The Law does not specifically refer to aquaculture.
Philippines	The Philippine Environment Code (1988) provides the foundation for all measures dealing with natural environment. Being a framework instrument, provides a chapter on fisheries and aquatic resources. The Philippine Fisheries Code (1998) provides for the development, management, conservation and utilization of fisheries and aquatic resources. The Code integrates all relevant laws to these issues. Part of Chapter II of the Code deals with aquaculture.	Fisheries Administrative Order n.º 214 (2001) establishes a Code of Practice for Aquaculture, outlining the general principles and guidelines for environmentally-sound design and operation to promote the sustainable development of aquaculture industry	Philippines is a party to the Convention on Biological Diversity (CBD). It has signed the Biosafety Protocol, but is not yet a party to the protocol. Philippines is also a party to the Convention on international Trade in Endangered Species of Wild Fauna and Flora (CITES). Philippines is a member of ASEAN and of Southeast Asian Fisheries Development Center (SEAFDEC)	Authorizations to engage and set up an aquaculture facility are granted by the body that has jurisdiction over the venue of the aquaculture operation. According to the Fisheries Code only 10 percent of the surface area of lakes and rivers may be allotted for the construction and operation of the structures for the culture of fish and other fishery products	The Fisheries Code requires that those, public or private, who intend to undertake activities or projects which will affect the quality of the environment to prepare a detailed Environment Impact Statement prior to undertaking such activity. Fishery projects are included in the list of the Environmental Critical Projects (Presidential Proclamation n.º 2146/1981)

TABLE 7
Relevant legislation – United States of America, Canada, Europe (including Member-States and associated states), the Republic of Chile, and New Zealand

Country	Basic Legislation	Guidelines and Codes of Conduct	International Arrangements	Authorization System	Environment Impact Assessment (EIA)
United States of America (USA)	In the USA, aquaculture is regulated at the federal and state level. In 1981, a comprehensive review of aquaculture across the USA identifies at least 120 federal laws that either directly (50) or indirectly (70) affected aquaculture, along with more than 1,200 state statutes regulating aquaculture in 32 states. • National Aquaculture Act (1980), establishes a National Aquaculture Development Plan and requires federal coordination of aquaculture activities; • Clean Water Act, the major federal law regulating environmental aspects of marine aquaculture; • Coastal Zone Management Act (1972), requires federal activities to be consistent with State Coastal Management Plans.	The EPA Effluent Limitations Guidelines and New Source Performance Standards for Concentrated Aquatic Animal Production Point Source; Draft Guidance for Aquatic Animal Production Facilities to Assist in Reducing the Discharge of Pollutants, EPA; EPA Animal Feeding Operations – Best Practices; Code of Conduct for Responsible Aquaculture Development in the United States of America Exclusive Economic Zone (NOOA 2003).	The USA is a party of several international agreements with implications for the regulation of aquaculture, namely the Convention on Biological Diversity, the Convention on International Trade in Endangered species of Wild Fauna and flora (CITES).	In principle, it is unlawful to conduct aquaculture operations or to culture approved species of aquatic plants and animals unless registered with state authorities. However, this may vary from state to state; The clean Water Act establishes pollution discharge permits and ocean discharge criteria; Open ocean aquaculture requires approval of United States of America Environmental Protection Agency, United States of America Army Corps of Engineers and National Marine Fisheries Service.	The requirement of an environment impact assessment before an aquaculture facility is registered may vary from state to state.

Country	Basic Legislation	Guidelines and Codes of Conduct	International Arrangements	Authorization System	Environment Impact Assessment (EIA)
Canada	The aquaculture industry is overseen in Canada by a combination of federal, provincial and local authorities. In recent years, both the federal and provincial governments have been striving towards a more efficient regulatory framework, balancing the need to protect the environment, sustain fisheries and enable a competitive industry to flourish.	The Canadian Aquaculture Industry Alliance, the umbrella organization for aquaculture associations in Canada, has developed the National Code System for Responsible Aquaculture. Another codes of conduct targeted specifically to the aquaculture industry have also been developed at the provincial level.	Canada is a party of several international agreements with implications for the regulation of aquaculture, namely the Convention on Biological Diversity, the Convention on International Trade in Endangered species of Wild Fauna and flora (CITES).	Both the federal and provincial governments are authorized to issue licences to engage in and set up an aquaculture facility in Canada, depending on whether the operation is located under federal or provincial territory. In the decision, the competent department will consider the potential impact of the aquaculture operation on wild fish, commercial and recreational fisheries, aboriginal fisheries and fish habitat	The Canadian Environmental Act (1992) (CEAA) and its regulations are the legislative basis for the federal practice of environmental assessment. Under the CEAA a marine aquaculture project is subject to an environmental assessment. The CeAA identifies the factors that must be considered in the screening of a project, including the environment effects, public consultation and measures to mitigate significant adverse environmental effects. The provinces also have jurisdiction over EIA for aquaculture.
European Union (EU)	• Water Framework Directive 2000/60/EEC of 23 October; • Marine Strategy Framework Directive 2008/56/EEC of 17 June; • Regulation (EC) n.° 710/2009 of 5 August; • Regulation (EC) n.° 535/2008 of 13 June; • Regulation (EC) n.° 708/2007 of 11 June; • Regulation (EC) n.° 506/2008 of 6 June; • Strategy for Sustainable Development of European Aquaculture COM(2002)511, of 19 February 2002 (Communication from the Commission to the Council and the European Parliament)	The Federation of European Aquaculture Producers(FEAP) is open to all national aquaculture associations. FEAP members adopt the 2000 Code of Conduct for European Aquaculture.	The EU is a member of several international arrangements, namely: •Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Agreement); •Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) Convention for the Marine Environment Protection and of the Mediterranean Coastal Area (Barcelona Agreement 1995). •North Atlantic Salmon Conservation Organization (NASCO). • Convention on Biological Diversity (CBD); •Convention on the Protection of the Marine Environment of the Baltic Sea Area (HELCOM); •International Baltic Sea Fishery Convention (IBSFC); • North Atlantic Fishery Organization (NAFO); • North East Atlantic Fishery Convention (NEAFC);	No specific legislation	Directive 85/377/EEC of 27 June 1985, modified by Directive 97/11/EEC of 3 March 1997.

Country	Basic Legislation	Guidelines and Codes of Conduct	International Arrangements	Authorization System	Environment Impact Assessment (EIA)
Denmark	The Fisheries Act (2004, as amended) regulates the management, control and development of fisheries and aquatic resources in Denmark.	There are no Guidelines or Codes of conduct.	Denmark is a member of the following international arrangements: •Party to the Convention on Biological Diversity (CBD); •North Atlantic Salmon Conservation Organization (NASCO).	According to the Fisheries act (2004), fish farming in Danish fisheries territories (ocean farming) can only take place if a licence has been granted by the Ministry of Food, Agriculture and Fisheries, a power that has been delegated to the Directorate of Fisheries. The Directorate determines the conditions, including possible time limits, for the licence. The Fisheries act (2004) applies to all kinds of fish farming, hence also for the fish farming of mussels, oysters etc., the setting up of aquaculture facilities placed on land using marine water, as well as for facilities using fresh water.	For new marine water fish farms, or those with considerably changes, if located outside a zone designated for aquaculture in the Regional Plan, an EIA shall be worked out. If the aquaculture facility is designated for intensive fish farming or has an intake of fresh water, an EIA shall be worked out as far as the facility it is likely to have a considerable impact on the environment, even when it is to be established in an aquaculture zone.
France	French aquaculture is ruled by two main sets of legislation, clearly separating inland and marine aquaculture. Inland aquaculture, coupled with inland fisheries, is regulated by the Environmental Code, while marine aquaculture must abide by marine fisheries legislation, among which are Law N.° 97–1051 on Maritime Fisheries and Mariculture (1997), and Decree of January 9th, 1852 on Maritime Fisheries (1852, as amended). The latter explicitly extends the applicability of its provisions to the farming of marine animals and plants.	The aquaculture sector is represented by several associations at national, regional and local level. The French Aquaculture Federation, being open to both freshwater and marine fish farmers, is the national fish farming association. At EU level, membership in FEAP (Federation of European Aquaculture Producers) is open to all national aquaculture associations. FEAP members adopt the 2000 Code of Conduct for European Aquaculture	France is a member of several international organizations, namely: •International Council for the Exploitation of the Sea (ICES); •Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES); • Convention on Biological Diversity (CBD) and the Biosafety Protocol Agreement; •Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Agreement); •Convention for the Marine Environment Protection and of the Mediterranean Coastal Area (Barcelona Agreement 1995).	The establishment of aquaculture facilities over private land requires the granting of an authorization, whereas a concession is necessary for the use of State-owned waterbodies.	The EIA system is regulated in Book I of the Environmental Code and in Decree N.° 77–1141 implementing article 2 of Law n.° 76–629 on the Protection of Nature (1977, as amended). The presentation of an EIA study is mandatory for the following aquaculture projects: •Salmon aquaculture farms. •Aquaculture farms with scientific or experimental purposes. •Fish farms with an annual production exceeding 2 tonnes or with a water surface over 3 hectares. •Fish farms intending to extend their production or surface to or over said thresholds.

Country	Basic Legislation	Guidelines and Codes of Conduct	International Arrangements	Authorization System	Environment Impact Assessment (EIA)
Germany	The most important federal acts in the field of water resources management (Federal Water Act and Federal Wastewater Charges Act) are only framework statutes. The water resources regulations in the Federal States (state water acts, state wastewater acts and various statutory orders) also contain important provisions which supplement the federal regulations or define them in greater detail. For example, the Federal States regulate ownership of waters, monitoring of waters, maintenance of waters, licensing procedures for uses of waters, and indirect discharges (i.e. discharges via wastewater treatment plants) into waters. The Federation participates in the discharge of responsibilities of the Länder, in the improvement of the agrarian structure and of coastal preservation including fisheries (Law on the Improvement of the Agrarian Structure and the Coastal Protection).	Guidelines have been developed for eco fish farming in ponds. Additionally, there are general guidelines for organic farming that have to be observed. A commission, partly formed by external experts, decides on the certification of farms on the basis of the observance of the guidelines. The certification refers to a whole farm, not to single products.	Germany is a party to the following international agreements: •Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR); • Convention on Biological Diversity (CBD); •Convention on the Protection of the Marine Environment of the Baltic Sea Area (HELCOM); •International Baltic Sea Fishery Convention (IBSFC); • North Atlantic Fishery Organization (NAFO); • North East Atlantic Fishery Convention (NEAFC); • North Atlantic Salmon Convention (NASCO).	Depending on the kind of project, a building permit might be necessary. A further authorization is required from nature conservation authorities for facilities in protected areas. An additional permit for fish farms has to be obtained from the fisheries administration of the Länder. Furthermore, before starting a fish farm, the regional offices in the Länder in charge, according to § 2 (1) of the Fish epidemics Regulation, have to be notified. The Federal Office for Maritime Navigation and Hydrography authorizes aquaculture and fish farm facilities in the exclusive economic zone and in high seas, according to the Sea Facilities Ordinance.	In Germany, EIA is not an independent administrative procedure but an integrated part of a licensing procedure (§2, 1 of the Act on Environmental Impact Assessment. The EIA provides for the description and assessment of the environmental effects of a project. In particular, the effects of a project on human beings, animals, plants, soil, water, air, landscape, including the relevant interactions, shall be determined. In addition, EIA must assess the effects on these assets in their completeness.

Country	Basic Legislation	Guidelines and Codes of Conduct	International Arrangements	Authorization System	Environment Impact Assessment (EIA)
Ireland	The main legal instrument is the Fisheries (Amendment) Act (1997), which has been further amended by the Fisheries (Amendment) Act (2001). Also relevant to aquaculture are the Foreshore Act (1933), the Foreshore (Amendment) Act (1992) and the Fisheries and Foreshore (Amendment) Act (1998), which require aquaculture project developers to obtain a foreshore licence before occupying or undertaking any works or placing structures on state-owned foreshore for the purpose of, inter alia, aquaculture. The foreshore is defined as the seabed and shore below the line of high water of ordinary or medium tides and extends outwards to the limit of 12 nautical miles.	In 2003, the Irish Sea Fisheries Board developed and introduced, the Environmental Code of Practice for Aquaculture Companies and Traders (ECOPACT) to promote the widespread introduction of Environmental Management Systems in the Irish aquaculture industry. The document lays out in detail the approach that should be taken, an overview of the legislation to be complied with and the extra measures and steps that the farmers can take to minimize the environmental impact of their operations in line with international best practices. Concerning stock health management, ECOPACT recommends implementing ISGA's Code of Practice for the Prevention of Stock Escapes of Irish Farmed Salmonids. In addition, ECOPACT also annexes and refers to the Code of Conduct for European Aquaculture of the Federation of European Aquaculture Producers (FEAP).	Ireland is a member of: • International Council for the Exploration of the Sea (ICES); • North Atlantic Salmon Conservation Organization (NASCO); • Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention); • Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES); I• Convention on Biological Diversity (CBD) and the Biosafety Protocol.	The Fisheries (Amendment) Act (1997) requires any person wishing to engage in land-based or marine-based aquaculture to apply for an aquaculture licence or, in the case of aquaculture in an investigative or experimental manner, for a trial licence. The Fisheries and Foreshore (Amendment) Act (1998) prohibits any person making an application from commencing aquaculture operations until duly licensed under the Fisheries (Amendment) Act (1997). Unlicensed operations could entail a fine and/or imprisonment.	According to the Aquaculture Regulations (1998), all applications for aquaculture or trial licenses in respect of seawater salmonid breeding installations shall be accompanied by an Environmental Impact Statement (EIS). An EIS may be required in other cases if the Minister considers that the proposed aquaculture is likely to have significant effects on the environment.

Country	Basic Legislation	Guidelines and Codes of Conduct	International Arrangements	Authorization System	Environment Impact Assessment (EIA)
Italy	From a constitutional point of view, fisheries and aquaculture are considered as matters of regional legislative competence. However, the reform process of the fisheries and aquaculture legislation was carried out by the Central Government, as required by the Parliament with Law n.° 57 of 2001 on the Opening and Regulation of Markets and Law n.° 38 of 2003 on Agriculture. With reference to the 2001 Law, the Government issued Legislative Decree n.° 226 of 2001 laying down Guidelines on the Modernization of the Fisheries and Aquaculture Sector. With regard to the 2003 Law, the Government issued Legislative Decree n.°154 of 2004 on the Modernization of the Fisheries and Aquaculture Sector and Legislative Decree n.°153 of 2004 on Marine Fisheries, which also amend certain provisions of the previous set of Legislative Decrees.	The Italian Agency for Environmental Protection and the Central Institute for Scientific and Technological Research Applied to the Sea drafted in 2001 the guidelines for the application of the EMAS Regulation (Parliament and Council Regulation (EC) n.°761/2001 allowing Voluntary Participation by Organizations in a Community Eco-Management and Audit Scheme) to the aquaculture sector.	Italy is a party of the following international agreements: • Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES); •Convention on Biological Diversity (CBD) and the Biosafety Protocol.; • Barcelona Convention of 1976 for the Protection of the Marine Environment and the Coastal Region of the Mediterranean.	At national level, the authorization system for the conduct of fisheries and off-shore aquaculture is regulated by Legislative Decree n.° 153 of 2004 on Marine Fisheries, which has repealed (together with Legislative Decree n.°154 of 2004 on the Modernization of the Fisheries and Aquaculture Sector) the Maritime Fisheries Law of 1965. Transitionally, the Regulation of 1968 (Decree of the President of the Republic, 2 October 1968, n.°1639), is still in force. Moreover, a concession is required for the use of the maritime State property and public inland waters, and for the construction of aquaculture facilities thereon.	The main piece of legislation concerning EIA is Law n.° 349 of 1986 establishing the Ministry of Environment, which provides for transitional procedural rules for the assessment of projects that are likely to significantly affect the environment. These shall be identified by Decree of the President of the Republic, upon proposition of the Ministry of Environment. The competent authority for the assessment at national level is the Ministry of Environment. However, the procedure requires the opinion of the Ministry for Cultural Heritage and Activities and of the concerned Regional Authority. Moreover, Law n.° 67 of 1988 establishes an EIA Commission with advisory and investigative functions.

Country	Basic Legislation	Guidelines and Codes of Conduct	International Arrangements	Authorization System	Environment Impact Assessment (EIA)
Portugal	The legal framework comprises Directive 2000/60/EEC of 23 October, which was encompassed by the Portuguese legislation through Law n.° 58/2005, of 29 December, complemented by Decree-Laws n.° 77/2006 of 30 March and n.° 226–A/2007, of 31 May). It defines the rules for sustainable water management, and applies to coastal, transitional and inland waters. It also comprises Decree-Law n.° 278/87 of 7 July, as amended by Decree-Law n.° 383/98 of 27 November and Regulatory Decrees n.° 14/2000, of 21 September and n.° 9/2008 0f 18 May, dealing with the aquaculture activity.	The European Federation of Producers (FEAP) has adopted a Code of Conduct for European Aquaculture, which is observed by its members. The main objective of this Code of Conduct is to promote the responsible development and management of aquaculture to ensure a high standard of quality in the production process, with consideration to both, environmental concerns and consumer demands. The Portuguese national professional association belongs to FEAP.	Portugal is a member of several international organizations, namely: •International Council for the Exploitation of the Sea (ICES); •Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES); •Agreement on the Biological Diversity (CBD).; •Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Agreement);	The establishment of aquaculture facilities over private land requires the granting of an authorization, whereas a licence is necessary for the use of State-owned waterbodies (water public domain).	The legal framework for the regulation of the Environmental Impact Assessment (EIA) procedure comprises Directive 85/377/EEC of 27 June 1985, modified by Directive 97/11/CE, which was encompassed by the Portuguese legislation through the Decree-Law n.° 69/2000, of 3 May. It establishes that projects of intensive aquaculture, with different outputs, depending on location (marine, estuarine or inland waters), are subjected to an EIA.

Country	Basic Legislation	Guidelines and Codes of Conduct	International Arrangements	Authorization System	Environment Impact Assessment (EIA)
Spain	The legal framework for the regulation and promotion of aquaculture consists of several legal instruments, amongst which outstand the Constitution of Spain, the Law for Promotion and Conservation of Riverine Fisheries (1942), the Law on Marine Aquaculture (1984) and the Law on the Coastline (1988). In agreement with the dispositions of the Constitution, the Autonomous Communities exert exclusive competence in inland waters, harvesting of shellfish, aquaculture, hunting and riverine fisheries. The legal instruments issued by the National Government on marine and inland aquaculture regulation have a general and supplementary character,	The European Federation of Producers (FEAP) has adopted a Code of Conduct for European Aquaculture, which is observed by its members. The main objective of this Code of Conduct is to promote the responsible development and management of aquaculture to ensure a high standard of quality in the production process, with consideration to both, environmental concerns and consumer demands. Some of the various Spanish professional associations belongs to FEAP The General Secretariat of Marine Fisheries, with the collaboration of the International Union for Nature (UICN) and the FEAP, has formulated the first of the "Directing Guidelines for the Sustainable Development of Aquaculture".	Spain is a member of several international organizations, namely: •International Council for the Exploitation of the Sea (ICES); •Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES); •Agreement on the Biological Diversity (CBD).; •Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Agreement); •Convention for the Marine Environment Protection and of the Mediterranean Coastal Area (Barcelona Agreement 1995).	Potential aquaculturists intending to undertake an aquaculture activity, either marine or inland, must apply for various authorizations or permits before the corresponding authorities. The applicable legal framework for the development of aquaculture falls under the Autonomous Communities which apply their own norms for the execution of the procedures of authorizations or leases. However, those Communities that haven't got their own norms, supplementary Law n.° 23/1984 of Marine Cultivation (for marine aquaculture), the Law of Riverine Fisheries of 1942 (for inland aquaculture), and Law n.° 22/1988 of the Coastline.	The legal framework for the regulation of the Environmental Impact Assessment (EIA) procedure comprises Directive 85/377/EEC of 27 June 1985, which was encompassed by the Spanish legislation through the Royal Legislative Decree n.° 1302/1986, of 28 June and the Royal Decree n.° 1131/1988, of 30 September, modified by Directive 97/11/CE. These modifications have been adopted through Law n.° 6/2001, of 8 May. It establishes that projects of intensive aquaculture with an output higher than 500 tonnes/year are subjected to an EIA whenever the environmental authority determines. The administrative procedure for EIA varies among the Autonomous Communities.

Country	Basic Legislation	Guidelines and Codes of Conduct	International Arrangements	Authorization System	Environment Impact Assessment (EIA)
Norway	The Aquaculture Act (2005) regulates the management, control and development of aquaculture in both inland and marine waters, as well as land based aquaculture. The purpose of the Act is "to promote the profitability and competitiveness of the aquaculture industry within the framework of a sustainable development and contribute to the creation of value on the coast. The agreement on the European Economic Area (EEA) imposes several obligations on Norwegian legislation.	There are no aquaculture guidelines/codes of conduct.	Norway is a party to the Convention on Biological Diversity (CBD) and to the Biosafety Protocol. Norway is also a party to the Convention on international Trade in Endangered Species of Wild Fauna and Flora (CITES).	The Aquaculture Act establishes an obligatory licensing system for aquaculture, and provides that the Ministry may, through regulations, prescribe limitations in the number of licences for aquaculture of salmon, trout and rainbow trout.	Any aquaculture licence may, as a general rule, only be granted if it is "environmentally responsible". A whole chapter of the Aquaculture Act is dedicated to environmental considerations, providing that aquaculture facilities shall be established, operated and abandoned in an environmental responsible manner. The Regulation relative to impact assessment (2005), establishes that an EIA is to be carried out for large aquaculture installations, if these activities may have significant effects on the environment, natural resources or community.
Chile	The Fisheries and Aquaculture Law (1989, as amended up to 2006) regulates the conservation of living aquatic resources, capture fisheries, aquaculture, as well as scientific and recreational fisheries.	There are no guidelines or codes of conduct on aquaculture.	Chile is a party to the Convention on Biological Diversity (CBD) but has not yet ratified the Biosafety Protocol. Chile is also a party to the Convention on international Trade in Endangered Species of Wild Fauna and Flora (CITES).	The authorization/concession system to set up aquaculture facilities is regulated by the General Fisheries and Aquaculture Law. An authorization or concession is not required for aquaculture activities carried out entirely on private property, even when inland or marine waters are used, provided they are used in accordance with the respective regulations.	In general, and according to the General Law on Environment, the conduct of aquaculture is subject to an environmental impact assessment, with the exception of minor scale aquaculture.

Country	Basic Legislation	Guidelines and Codes of Conduct	International Arrangements	Authorization System	Environment Impact Assessment (EIA)
New Zealand	The Resources Management Act (RMA) as amended in 2004, provides much of the framework for managing aquaculture. Under the RMA, the Minister of Conservation is responsible for preparing coastal policy statements, approving regional coastal plans and permits for restricted coastal activities. Freshwater aquaculture activities are regulated by the Freshwater Fish Farm Regulations of 1983, under the statutory guidance of the Fisheries Act as amended in 2004.	New Zealand as not adopted a specific code of conduct for fisheries or aquaculture. However, it "fully supports" the FAO Code of Conduct for Responsible Fisheries	New Zealand is a party of several international agreements with implications for the regulation of aquaculture, namely the Convention on Biological Diversity, the Convention on International Trade in Endangered species of Wild Fauna and flora (CITES).	The RMA establishes that aquaculture activities are restricted to designated areas, called aquaculture management areas (AMA). The regional council develops regional plans and policy statements, in order to manage coastal resources, including aquaculture. The rules and plans will determine whether resource consents are required to carry out aquaculture related activities in a coastal zone. Inland fish farming is also subject to an approval from the local authority, in the form of a resource consent or certificate compliance	The RMA requires that any application for a resource consent must contain an adverse effects assessment, which details the scale and significance of the effects of aquaculture and other activities, upon the environment.

Carrying capacity tools for use in the implementation of an ecosystems approach to aquaculture

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Abstract

The development of carrying capacity indicators and models is progressing rapidly. A framework for defining four different types of carrying capacities has been developed, and a review of available shellfish and cage finfish models has been completed indicating new examples of potential decision-making tools for the spatial planning and the ecosystem-based management of aquaculture. The ability to estimate different types of carrying capacities is a valuable tool for decision-makers and the public when assessing the impact of development and expansion of aquaculture operations, and can be of good use to help develop more sophisticated spatial plans and multiple uses of aquatic space that include aquaculture. Development of more refined-and inclusive-carrying capacity frameworks and models will help organize the many available indicators and metrics, plus allow improved tracking of communications about, and sectoral progress towards, an ecosystems approach to aquaculture.

Introduction

Aquaculture is growing rapidly in inland and coastal regions throughout the world, most notably in Asia (People's Republic of China, the Kingdom of Thailand, the Socialist Republic of the Socialist Republic of Viet Nam, the People's Republic of Bangladesh, the Republic of India) and Latin America (the Federative Republic of Brazil, the Republic of Chile) (Costa-Pierce, 2010; FAO, 2009). Rapid growth has fuelled concerns over the ecological and social impacts of aquaculture in crowded inland and coastal areas rife with user conflicts where "new" uses such as aquaculture compete for space and resources with traditional users of land, water, and coasts. FAO has estimated an increased growth of aquaculture to 2030

of at least 50 million metric tons, raising further concerns over resource use in aquaculture (Costa-Pierce *et al*. 2012).

It is now widely recognized that further aquaculture developments need to be planned and designed in a more responsible manner that minimize as much as possible negative social and environmental impacts. The European Union Water Framework, Marine Strategy Directives, the Canadian Oceans Act, and the US National Policy for the Stewardship of the Ocean, Coasts, and Great Lakes all call for spatial planning for human activities such as aquaculture to be carried out in a more sustainable fashion, including the essential components of: (i) knowledge-based approaches for decision-making, and (ii) ecosystem-based approaches for integrated management.

In 2006 the Fisheries and Aquaculture Department of the Food and Agriculture Organization (FAO) of the United Nations recognized the need to develop an ecosystem-based management approach to aquaculture similar to the Code of Conduct for Responsible Fisheries. FAO (Soto *et al.*, 2008) suggested that an ecological approach to aquaculture (EAA) would have three main objectives: human well-being, ecological well-being, and the ability to achieve both via more effective governance within a hierarchical framework that was scalable at the farm, regional, and global levels. In 2008, FAO defined an EAA as a ***strategy for the integration of aquaculture within the wider ecosystem such that it promotes sustainable development, equity, and resilience of interlinked social-ecological systems***. Three principals were adopted, and key issues developed at the different scales of society; with principle #1 being a key driver, that ***aquaculture should be developed in the context of ecosystem functions and services (including biodiversity) with no degradation of these beyond their resilience capacity*** (Soto *et al.*, 2008). Defining, developing, and adapting existing methods to estimate resilience capacity, or the limits to "acceptable environmental change" are essential tasks to moving forward with an EAA.

Determinations of "acceptable change" have both natural and social science components. Many terms has been used to estimate these, including "environmental carrying capacity", "environmental capacity", "limits to ecosystem function", "ecosystem health", "ecosystem integrity", "fully functioning ecosystems", etc., all of which are subject to an intimate knowledge of not only natural ecosystem science, but also social-cultural and political factors (Hambrey and Senior, 2007). Environmental impact assessments bracket only some of these issues.

Concepts of carrying capacity

A goal of aquaculture management is to have tools available that can predict and measure the capacity of an area to support a cultured species. Carrying capacity is an important concept for ecosystem-based management which helps define the upper limits of aquaculture production and ecological limits, and the social acceptability of aquaculture without causing "unacceptable change" to both natural ecosystem and social functions and structures. Kaiser and Beadman (2002) defined carrying capacity as the potential maximum production a species or population can maintain in relation to available resources. Assessment of carrying capacity is one of the most important tools for technical assessment of not only the environmental sustainability of aquaculture since it is not limited to farm or population sizes issues but also can be applied to ecosystem, watershed, and global scales.

Inglis, Hayden and Ross (2002) and McKindsey *et al.* (2006) defined four different types of carrying capacities (physical, production, ecological and social), and found that, with few exceptions, carrying capacity work has focused on determinations of production carrying capacity, which is the maximum sustainable yield of cultured organisms that can be produced within an area. Although these accepted definitions were originally described for bivalve aquaculture, they have also been applied to finfish cage culture (Gaĉek and Legović, 2010).

Physical carrying capacity assumes the entire waterbody is leased for aquaculture, being little more than the total area suitable for aquaculture. Inglis, Hayden and Ross (2002) and McKindsey *et al.* (2006) note that the notion of physical carrying capacity does not inform about at what density cultured organisms are stocked, or their production biomass. Physical carrying capacity is useful to quantify potential area available for aquaculture in the ecosystem, but it offers little information towards determinations of aquaculture's limits at the waterbody or watershed level in the EAA.

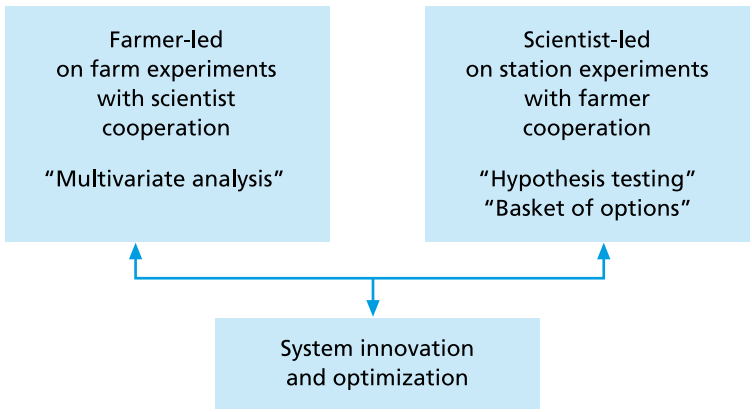
Production carrying capacity estimates maximum aquaculture production and is typically considered at the farm scale. However, production biomass calculated at production carrying capacity could be restricted to smaller areas within a water basin so that the total production biomass of the water basin does exceed that of the ecological carrying capacity.

Ecological carrying capacity is defined as the magnitude of aquaculture production that can be supported without leading to significant changes to ecological processes, species, populations, or communities in the environment. Gibbs (2007) discussed a number of issues pertaining to the definition and calculation of ecological carrying capacity and highlighted the fact that shellfish aquaculture can have an impact on the system by being both consumers (of phytoplankton) and producers (by recycling nutrients and detritus) with the concomitant ecosystem impacts of both. In determining ecological carrying capacity he has urged caution when attributing cause of change (and partitioning impacts) between shellfish farm activities and other activities in the ecosystem.

When modelling is combined with stakeholder input, the resulting ecological carrying capacity calculations are exceptionally powerful in the management arena (Byron *et al.*, 2011c). Science is much more likely to be accepted if there are agreed upon, cooperative, aquaculture research frameworks that combine efforts of scientists and farmers (Figure 1), and are well integrated into outreach and extension services so that model results are adopted into management, and stakeholders have had direct input into and obtain an intimate knowledge of the science (Costa-Pierce, 2002). Efforts to improve methodologies for determining social carrying capacity may be well served to consider approaches that integrate rigorous science into participatory extension processes that include and measure the quality of participation and stakeholder inputs (Dalton, 2005, 2006).

Social carrying capacity has been defined as the amount of aquaculture that can be developed without adverse social impacts. Byron *et al.* (2011c) has stated that the ultimate goal of determinations of social carrying capacity is to quantify the value of stakeholder involvement in a science-based effort to determine the proper limits to aquaculture in their local waters. Ecological degradation or adverse changes to ecosystems due to aquaculture may inhibit social uses. The point at which alternative social uses become prohibitive due to level, density, or placement of aquaculture farms is the social carrying capacity of aquaculture (Byron *et al.*, 2011c). Social carrying capacity was been

FIGURE 1
Aquaculture cooperative research and extension for innovation

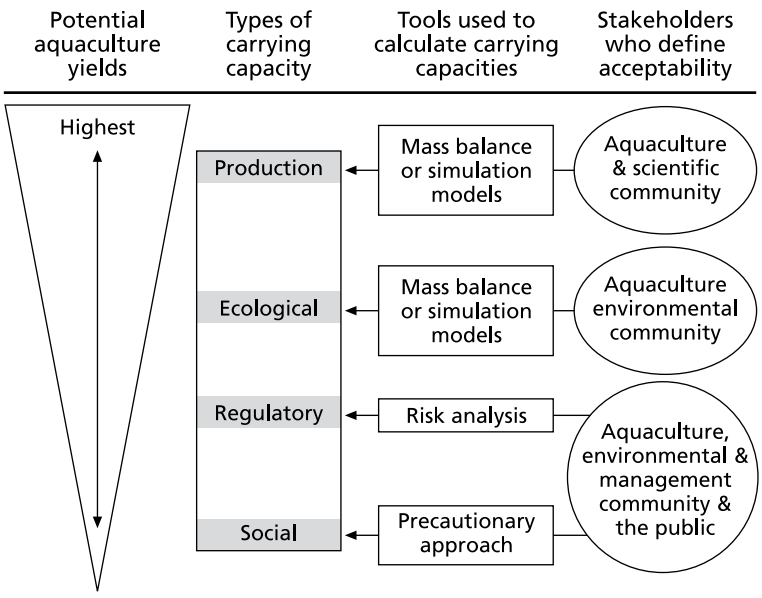


Source: Costa-Pierce (2010).

determined for Rhode Island (United States of America) waters through a stakeholder process (Byron *et al.*, 2011c) that included commercial fishing, recreational fishing, environmental groups, academia, riparian land owners, policy-makers, and other groups who agreed upon a level of shellfish aquaculture that would not restrict or inhibit use to any group.

Analytical methods for calculating social carrying capacity are still in development. Gibbs (2007) recognized the importance of economics in carrying capacity determinations and defined an "economic carrying capacity" as the "the amount of money investors are willing to invest, and the monetary value associated with sellable products and ecosystem services". Kite-Powell (2009) placed a monetary value on various ecosystem uses and calculated the social carrying capacity at which relative value for all uses were maximized. This included assigning value not only to commercial products but also to ecosystem services and other intrinsic and tacit values associated with the system or use of the system.

FIGURE 2
A framework of different types of carrying capacities for aquaculture, tools being used, and stakeholder groups involved



Source: Costa-Pierce (2010).

Note: Highest aquaculture yields occur when models predict maximum farm production for given input variables, and ecological, regulatory and social concerns are less. Potential aquaculture yields decrease as ecological, regulatory and social concerns are equal to or exceed the importance of aquatic food production. In North America and Europe, social carrying capacity drives determinations of production carrying capacity in aquaculture, and there is a strong interaction between all types of carrying capacities; elsewhere in the world such limits on production carrying capacity are much less, but are also increasing.

Every definition has a purpose for a specific situation. Ecological and social carrying capacities are unique in that they depend on social values (McKindsey *et al.*, 2006). It is up to the stakeholders to define how much change in ecosystems they are willing to accept (Byron *et al.*, 2011c). Interactions of some differing types of carrying capacities discussed here with the scientific tools being used, and the interest groups who define "acceptability" of aquaculture are described in the framework presented (Figure 2). Regulatory carrying capacity is added as a new type and defined by rigorous risk analysis and communication protocols (GESAMP, 2008).

To implement an ecosystem approach to sustainable aquaculture, carrying capacity methods are only one of several tools needed. A review of available tools for assessment of sustainability in aquaculture is presented (Table 1), but is not exhaustive as metrics such as Ecological Footprinting (Wackernagel, 1994; Wackernagel and Rees, 1996), Primary Productivity Required (Talberth *et al.*, 2006), Energy Flow (Sangwon, 2005), and Virtual Water Flow (Hoekstra *et al.*, 2009) analyses have increasingly been used to judge the overall sustainability of aquaculture versus other primary food production practices (Welch *et al.*, 2010).

TABLE 1
Sustainability science toolkit appropriate to an ecosystems approach to aquaculture (Costa-Pierce and Page, forthcoming).

Social sustainability	Environmental sustainability	Economic sustainability
Stakeholder analysis: analysis of attitudes of stakeholders at the initiation of and throughout a project. Allows tracking of how stakeholders change attitudes over time with educational processes (Fletcher *et al.*, 2003; Savage *et al.*, 1991; Hemmati *et al.*, 2002; Dalton, 2005, 2006) **ISO 26000 guidelines** for corporate social responsibility (ISSD, 2004) **ICLEI** (International Council for Local Environmental Initiatives) provides software and tools to help local governments achieve sustainability goals (www.iclei.org)	**Life cycle analysis:** complete assessment of products from raw material production, manufacture, distribution, use and disposal, including all transportation; used to optimize environmental performance of a single product or a company. A similar analysis called a MET (Materials, Energy, and Toxicity) Matrix is also used (American Center for Life Cycle Assessment www.lcacenter.org; Bartley *et al.*, 2007; Ayer and Tyedmers, 2009) **ISO 14000 certification:** norms to promote more effective and efficient environmental management and provide tools for gathering, interpreting and communicating environmental information (Interrnational Organization for Standardization (ISO), www.iso.org/iso/iso_14000_essentials) **Environmental impact assessment:** the process of identifying, predicting, evaluating, mitigating biophysical, social, and other effects of development proposals prior to policy decisions (Environmental Impact Assessment Review, www.elsevier.com/wps/find/journaldescription.cws_home/505718/description#description; IAIA, 1999) **Environmental indicators:** the use of quantitative indicators of resource use, efficiency and waste production in aquaculture (Boyd *et al.*, 2007)	**Cost-benefit analysis:** analysis of cost effectiveness of different uses to determine if benefits can outweigh costs (US Federal Highway Administration) www.fhwa.dot.gov/planning/toolbox/costbenefit_forecasting.htm **Triple bottom line or "full cost" accounting:** costs considered for all environmental, economic, and social impacts; costs measured in terms of opportunity costs (the value of their best alternative use); guiding principle is to list all parties affected and place a monetary value on effects on welfare as valued by them (Savitz and Weber, 2006; McCandless *et al.*, 2008)

Models to determine shellfish carrying capacity

Environmental concerns regarding shellfish aquaculture are related primarily to how aquaculture interacts with, and potentially controls, fundamental ecosystem processes at the base of the aquatic food web. Shellfish also excrete large quantities of ammonia, and biodeposit organic matter on the seabed causing impacts on benthic habitats, which, depending on the intensity of culture, can cause adverse impacts in some regions. McKindsey *et al.* (2006, 2009) and Weise *et al.* (2009) attempted to model impacts of mussel biodeposition on the benthos. Such models provide useful information in determinations of the carrying capacity of a site. McKindsey *et al.* (2006) and Callier *et al.* (2009) provided quantifiable evidence that benthic species richness will decrease with increasing biodeposition, and found that some organisms can be good indicators of environmental stress, both by their presence (tolerance) and extirpation (sensitivity). Results of this manipulative experiment are an important step towards evaluating the environmental carrying capacity of sites for bivalve aquaculture.

Many models have been generated to assess carrying capacity relating to shellfish aquaculture, ranging from simple model approaches developed to determine the risk of bay-scale phytoplankton depletion from excessive bivalve grazing (production carrying capacity) to full ecological models with subsequent estimates of shellfish production and ecological carrying capacity (Table 2). Most models are estimates of single species capacity within an ecosystem, assessments of the relative risk of culture activities in different settings, or models developed to optimize shellfish yields in a leased area.

TABLE 2
Carrying capacity models for use in the implementation of an ecosystems approach to shellfish aquaculture.

System	Carrying Capacity type	Model framework	Management application	Reference
Oosterschelde estuary, Netherlands	production	empirical study: correlate current velocity and shellfish biomass with seston depletion	none	Smaal *et al.*, 1986
Nova Scotia, Canada	production	empirical study: divided food filtered by food available	none	Carver and Mallet, 1990
Marennes-Oléron Bay, France	production	coupled physical and biological submodels into an ecological model	none	Raillard and Ménesguen 1994
Carlingford Lough, Ireland	ecological and production	coupled circulation, primary production, and oyster growth model	none	Ferreira, Duarte and Ball, 1997
Marennes-Oléron Bay, France	production	model based on physical transport and deposited matter	none	Bacher *et al.*, 1998
Carlingford Lough, Ireland	production	population dynamics model	none	Bacher *et al.*, 1998
Carlingford Lough, Ireland	production	one-dimensional ecosystem box model including physical and biological processes	none	Ferreira, Duarte and Ball, 1998
na	ecological and production	Conceptual	none	Smaal *et al.*, 1998
Takapoto Atoll, French Polynesia	ecological	inverse analysis of carbon flow in lower trophic levels	none	Niquil *et al.*, 2001
Oosterschelde estuary, Netherlands	production	empirical study	none	Smaal, van Stralen and Schuiling, 2001
Sungo Bay, Shandong Province of China	ecological	coupled two-dimensional circulation-biogeochemical model	potential	Duarte *et al.*, 2003
Thau lagoon	ecological	population model for oysters and mussels	none	Gangnery *et al.*, 2003
Sanggou Bay, Northern China	ecological and production	individual-based species models and multi-cohort population models	potential	Nunes *et al.*, 2003
Tasman and Golden Bays, New Zealand	ecological and production	EcoPath: linear food web	none	Jiang and Gibbs, 2005
Northern Irish Lough System	ecological, production, and social	circulation, biogeochemical, bivalve growth, production, and eutrophication	potential	Ferreira *et al.*, 2007
Lagune de la Grande-Entrée, Iles-de-la-Madeleine, Québec. Magdalen Islands in the central Gulf of St. Lawrence in eastern Canada	ecological and production	coupled biological-circulation-chemical model	none	Grant *et al.*, 2007
Mont Saint Michel Bay, Normand-Breton Gulf (English Channel), France	ecological	two-dimensional coupled circulation-sediment model, lower trophic-level model, and bivalve-filtration model	potential	Cugier *et al.*, 2008
Carlingford, Strangford, and Belfast loughs in Northern Ireland	ecological, production, and social	coupled circulation, lower trophic level, individual-based bivalve growth, and population models	potential	Ferreira *et al.*, 2008a

System	Carrying Capacity type	Model framework	Management application	Reference
Xiangshan Gang, China	production	integrated systems analysis using dynamic coupling of economic drivers with ecological models with emphasis on polyculture	potential	Ferreira *et al.*, 2008b
Sanggou Bay, Northern China	production	integrated systems analysis using dynamic coupling of economic drivers with ecological models with emphasis on polyculture	potential	Ferreira *et al.*, 2008b
Huangdun Bay, China	production	integrated systems analysis using dynamic coupling of economic drivers with ecological models with emphasis on polyculture	potential	Ferreira *et al.*, 2008b
Scottish Lochs	ecological	coupled circulation, lower trophic level, and bivalve-growth models	used to determining license-level activity	Gubbins *et al.*, 2008
Sanggou Bay, Northern China	ecological and production	coupled ecosystem-physiology-circulation and bivalve-growth models	potential	Sequeira *et al.*, 2008
Xiangshan Gang, China	ecological and production	coupled ecosystem-physiology-circulation and bivalve-growth models	potential	Sequeira *et al.*, 2008
Carlingford Lough, Ireland	ecological and production	coupled ecosystem-physiology-circulation and bivalve-growth models	potential	Sequeira *et al.*, 2008
Loch Creran, Scotland	ecological and production	coupled ecosystem-physiology-circulation and bivalve-growth models	potential	Sequeira *et al.*, 2008
Tracadie Bay, Prince Edward Island, Canada	ecological and production	dynamic ecosystem box-model	potential	Cranford, Hargrave and Doucette, 2009; Filgueira and Grant, 2009
Loch Creran, Scotland	ecological, production, and social	coupled circulation, lower trophic-level, bivalve-growth, population, and financial an profit models	potential	Ferreira *et al.*, 2009
Pertuis Brenton, France	ecological, production, and social	coupled circulation, lower trophic-level, bivalve-growth, population, and financial an profit models	potential	Ferreira *et al.*, 2009
Bay of Piran, Slovenia	ecological, production, and social	coupled circulation, lower trophic-level, bivalve-growth, population, and financial an profit models	potential	Ferreira *et al.*, 2009
Chioggia, Italy (Adriatic coast)	ecological, production, and social	coupled circulation, lower trophic-level, bivalve-growth, population, and financial an profit models	potential	Ferreira *et al.*, 2009
Ria Formosa, southern Portugal	ecological, production, and social	coupled circulation, lower trophic-level, bivalve-growth, population, and financial an profit models	potential	Ferreira *et al.*, 2009
Great-Entry and House Harbor lagoons on Magdalen Islands and Cascapedia Bay, Quebec, Canada	ecological and production	coupled circulation and sediment models (DEPOMOD; Cromey, Nickell and Black, 2002)	potential	Weise *et al.*, 2009
Narragansett Bay, Rhode Island, United States of America	ecological and production	EcoPath: linear food web	potential	Byron *et al.*, submitted
Coastal Ponds, Rhode Island, United States of America	ecological and production	EcoPath: linear food web	potential	Byron *et al.*, submitted

Most models have assumed shellfish to be the equivalent of "aquatic cows", grazing almost exclusively on standing stocks of phytoplankton and algae. However, cultured bivalve species have an exceptional capacity to filter large volumes of water containing not only phytoplankton, but also, zooplankton, detritus and other suspended particulate matter (Ferriera *et al.*, 2008a). In Ireland it has been estimated that shellfish remove 4 X more detritus than phytoplankton (Ferriera *et al.*, 2007). Byron *et al.* (2011b) found that in a highly productive temperate bay (Narragansett Bay, R.I., United States of America) that 71 percent of the total energy flow of the ecosystem originated from detritus, and that large quantities of shellfish aquaculture could be supported sustainably with incremental decreases in the large detrital pool. A review of some of the more important models is warranted:

- Cranford *et al.* (2007), Cranford, Hargrave and Doucette (2009) and Grant *et al.* (2008) presented new methodologies for mapping the "depletion plume" from shellfish aquaculture and showed that significant phytoplankton depletion from extensive mussel culture activities in Tracadie Bay (Canada) occurred. Studies showed that mussel aquaculture embayments in Prince Edward Island (Canada) were at a high risk of significant bay-wide particle depletion from mussel culture and that succession had occurred to the point where these bays were dominated by picophytoplankton (0.2–2.0 µm cell diameter). Large-scale removal of larger phytoplankton by mussels occurred, causing significant ecological destabilization that would be expected to alter predator-prey and competition interactions between resident species.
- Jiang and Gibbs (2005) developed an Ecopath model for a marine ecosystem where large-scale expansion of mussel aquaculture was proposed. They defined ecological carrying capacity as significant changes in modelled energy fluxes or the structure of the food web. The model estimated the mussel production capacity in New Zealand at 350 tonnes/km^2/year; however, ecological carrying capacity models reduced bivalve production to 65 tonnes/km^2/year.
- Ferreira, Hawkins and Bricker (2007) developed the Farm Aquaculture Resource Management (FARM) model to be used by both the farmer and regulator to analyze culture location and species selection, and to assess farm-related eutrophication effects. FARM allows ecological and economic optimization of culture practice including timing and sizes for seeding and harvesting, densities, and spatial distributions. This modelling framework combines physical and biogeochemical components as well as bivalve growth models for determining shellfish production. It can be applied to multiple bivalves species and polyculture. FARM is a useful valuation methodology for integrated nutrient management in coastal regions.
- Grangeré *et al.* (2008) developed an ecosystem box model of the nitrogen cycle in the Baie des Veys, the French Republic and concluded that oyster aquaculture had the most impact on phytoplankton and suspension feeders. Higher grazing pressure on phytoplankton by cultured oysters as well as the trophic competition occurred, indicating shellfish biomass was beyond the ecological carrying capacity. Analysis of annual variability indicated that ecosystem fluxes varied with external river inputs. The influence of cultivated oysters seemed to be more important than other environmental factors beyond a threshold value of river inputs around 3 000 tonnes N/year. In the Baie des Veys, river inputs were seldom lower than 3 000 tonnes N/year, so, the nitrogen cycle in the Baie des Veys was influenced more by the cultivated oysters than by the environment.
- Cugier *et al.* (2008) examined trophic interactions in Baie Mont-Saint-Michel (the French Republic) by developing coupled biological and hydro-sedimentary models to examine the relative ecological roles of wild, cultured, and invasive filter-feeders. They concluded that filter-feeders controlled chlorophyll levels.

If all filter feeders were removed from the bay, maximum chlorophyll would be 2–3X higher in most parts of the bay. The invasive gastropod, *Crepidula fornicata* was deemed to have a dominant effect in the western bay, where this species is concentrated, while wild filter-feeders had their main effect in the east. Filtration pressure appears to be partially compensated by the production and deposition of organic matter (feces and pseudo feces) by cultivated and invader species. Demineralization of this matter was able to sustain chlorophyll levels.

- Weise *et al.* (2009) applied numerical models to the distribution of biodeposits around mussel lines (shellfish-DEPOMOD) and predicted near-field effects at a high resolution (meter-scale). Since shellfish culture sites are typically located in shallow coastal areas, this type of resolution is important to model dispersion of biodeposits over fairly short distances. This model, in conjunction with other models/indices that focus on far-field effects (e.g. nutrient cycling, pelagic carrying capacity), provide industry and ocean managers with the tools to efficiently and comprehensively assess effects associated with shellfish culture activities within an ecosystem-based management framework.

Byron *et al.* (2011a, b and c) developed Ecopath models for decision-makers considering the carrying capacity of oyster aquaculture in Narragansett Bay (United States of America). Current biomass was found to be 0.47 tonnes/km^2/year. The ecological carrying capacity was found to be 297 tonnes/km^2/year (625 X current harvests). Approximately 38 950 tonnes of shellfish or 13X the current total could be harvested without exceeding the ecological carrying capacity (Byron *et al.*, 2011a). At production carrying capacity, 3 481 tonnes/km^2/year are possible or 1 235 897 tonnes/year for Narragansett Bay. If farming was limited to 3 481 tonnes/km^2/year across only 9 percent of the area of the Bay, this would still be below the ecological carrying capacity.

Models to determine cage fish carrying capacity

In the 1990's determinations of carrying capacity for cage aquaculture were made using statistical models based upon empirical data (Beveridge, 1993). The driver for determinations of carrying capacity was the increasing concern about the environmental impacts of cage aquaculture in smaller, enclosed, poorly flushed waterbodies due to impacts of nutrients and waste feeds on not only pelagic and benthic ecosystems, but also due to increased user and other social conflicts. Such dramatic environmental-social concerns over the poorly planned and regulated expansion cage culture occurred in dramatic fashion as evidenced by the major "boom and bust" cycles of cage aquaculture in the Republic of the Philippines (Laguna be Bay and the 7 lakes of San Pablo; Beveridge, 1993), in Indonesian reservoirs (Costa-Pierce, 1998), and trash-fish-fed cage culture in many Asian countries (Pullin, Rosenthal and MacLean, 1993).

Over the past decade numerous simulation models have been developed to predict environmental changes with different nutrient loadings from dissolved and particulate inputs from fish cage aquaculture (Table 3). With one exception (CADS_TOOL, which makes economic predictions from site specific data), all of these modelling tools remain focused on providing information and predictions on how the environment would respond to various siting and production levels for fish culture aquaculture. Important input variables from physical oceanography and limnology are used to weigh morphometric, stratification, water flow and current data along with biological factors such as aquaculture feed inputs, consumption, and waste production that help predict changes in ecosystem trophic state and functioning of the pelagic and benthic environment due to fish cage aquaculture. In summary, most scientific work to develop tools to provide information to measure the carrying capacity of fish cage aquaculture appears to have only informed discussions of production and ecological carrying capacities.

TABLE 3
Selection of important models for use in determinations of carrying capacity in the implementation of an ecosystem approach to cage culture of finfish

Models/Tools	Objectives	Carrying capacities	Sources
Statistical models	Assimilation capacity of the environment is calculated based upon discharges; Assessments of aquaculture carrying capacities are made on levels of unacceptable water quality and/or benthic environmental impacts	Ecological carrying capacity	Beveridge (1993); Huiwen and Yinglan (2007)
Site selection framework	Aggregates, weights and ranks criteria for determinations of siting cages in offshore waters	Regulatory and Social carrying capacities	Benetti *et al.* (2010)
3D Tidal Model	Calculates site placement, spatial distribution of cages, and number of cages	Ecological carrying capacity	Gaĉek and Legović (2010)
CADS_TOOL (Cage Aquaculture Decision Support Tool)	Site selection, site classification, site economic appraisal	Production and Regulatory carrying capacities	Halide (2009; http://data.aims.gov.au/cads)
DEPOMOD and AUTODEPOMOD	Site selection from current velocity and direction, depth, feed input and cage plans. Predictions of waste fecal and feed deposition and benthic impact.	Production and Regulatory carrying capacities	Cromey, Nickell and Black (2002); SEPA (2005); www.sepa.org.uk/aquaculture/modelling
MERAMOD and TROPOMOD	DEPOMOD for Mediterranean and tropical species	Production carrying capacity	www.philminaq.eu
MOM (Modelling-Ongrowing fish farms-Monitoring)	Stocking capacities determined by modelling preservation of water quality and benthic ecosystem integrity	Production carrying capacity	Erivk *et al.* (1997); Hansen *et al.* (2001); Stigebrandt *et al.* (2004)
AquaModel	Models determine fish cage biomass impacts on pelagic and benthic ecosystems	Ecological carrying capacity	Rensel *et al.* (2007); www.aquamodel.org

Recommendations

McKindsey *et al.* (2006) in their review found that the vast majority of modelling efforts undertaken to assist managers with information on aquaculture's impact on the environment considered only one or a limited number of ecosystem components. McKindsey *et al.* (2006) and the International Council for the Exploration of the Sea (ICES, 2008) identified gaps in knowledge that need to be addressed in order to advance progress in the scientific basis of carrying capacity for aquaculture, including:

- Development of specific guidance to better define "unacceptable" ecological impacts that include stakeholder identification of important ecological attributes and ecosystem components.
- Identification of critical limits (i.e. performance standards or thresholds) at which the levels of aquaculture developments disrupt and ecosystem, thus requiring management actions.
- Development of spatially explicit time-series of ecological responses to aquaculture development and validation of model predictions.

- Identification of site-specific factors affecting ecological carrying capacity.
- Development of models that consider temporally variable activities (e.g. seasonal harvesting).
- Validation of models be conducted across a range of habitat and culture conditions in order to assess their general applicability.

A great opportunity for the future is to use aquaculture carrying capacity models to complement aquatic spatial planning and management. In addition, the better use of carrying capacity models for management will help better refine the roles of use of aquaculture risk assessment and communications protocols for aquaculture (GESAMP, 2008), and a more rational application of the precautionary approach.

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Socio-economic factors affecting aquaculture site selection and carrying capacity

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Abstract

The location of aquaculture activities has historically been based on a combination on local demand and agro-ecology, with global demand and deteriorating capture fishery stocks having an increasing influence. External interventions aimed at stimulating aquaculture in developing countries have often been driven by geography and objectives with little regard for other key criteria for successful aquaculture, often resulting in limited development and sustainability. Attempts to restrict certain types of aquaculture or limit them within zones have often failed, especially in countries with weak governance. Aquaculture has potential to exert significant social and economic impacts through upstream and downstream links around the use of chemicals, wastes expelled, and stock migration. This incorporates a broad section of people as stakeholders. Similarly, employment along the value chains, both upstream and downstream, bring benefits to many not directly involved in farming. They considered that focus in development programs should be placed on identifying and responding to local factors, rather than allowing top-down, external factors to dominate. Community stakeholder engagement needs to be strengthened, with more rigorous application of cost benefit analysis. Alongside immediate economic concerns, a broad understanding of the social and ecosystem services that are part of aquaculture and associated value chains must be considered.

Introduction

The factors that explain the occurrence and relative importance of aquaculture spatially relate to its historical development based on local demand and suitable agro-ecology and, more recently on a rapid increase in international demand for certain categories of seafood. This latter trend has been accelerated by the continuing deterioration in global fisheries but also by the comparative advantage of consistent quality, supply and price of farmed seafood reaching consumers. Investment, governance and market development also explain the current status. Thus although the specific physical conditions of the Norwegian and Scottish coastlines and fishery

infrastructure predisposed these areas as suitable for salmonid culture, investment in strategic research, legal access to water and land resources and the development of new markets have rapidly transformed small initial enterprises to global entities. It has been suggested that access restrictions and competition with other uses are now one of the key reasons for stagnation of the EU aquaculture sector (Bostock *et al.*, 2009). Shrimp development around the coastlines of Asia and Latin America has also been stimulated by increased demand for these erstwhile luxury products in developed country markets. Here weak governance and dynamic commercial actors (Goss, Burch and Rickson, 2000; Lebel and Anderies, 2006) has resulted in uncoordinated development during the early stages of evolution in these sectors. Attempts by Government to geographically constrain development, for a variety of reasons, have had limited impacts. Experience suggests that major behavioural change has been stimulated by environmental shocks causing major economic loss. Such changes suggest that lessons can be learned and given favourable institutional conditions that sustainability can be progressively improved. The tripartite loch agreements (between the private sector, the state and local communities) have contributed to reduced incidence of salmon disease in mainland Scottish lochs for example.

The development of aquaculture has often been linked to actions and policies outside the immediate sector. Important among these have often been organizations responsible for governance of water and land development. The Water Boards in the People's Republic of Bangladesh (Haque, Little and Murray, 2011), which has had major impacts on the development of the shrimp and prawn industry in the Southwest of the country, and the Kingdom of Thailand that help set the course for development of the Chaopraya Delta as a major aquaculture zone (Molle, 2007) are examples. Such stakeholders with little direct interest in aquaculture have had profound impacts through their actions of its form and function.

External interventions by Government or non- Government organizations to stimulate aquaculture have become a common aspect of broader rural development. These have sometimes been limited to establishing hatcheries to provide a more consistent source of juveniles or to provide more comprehensive services to early adopters but they have generally had a clear geographical focus. Such initiatives in Sub Saharan Africa (SSA) over the last 20–30 years have often been as a result of the aims and objectives of international donor agencies and associated SSA government ministries that have had a poverty alleviation mandate. Many such projects were, and to a certain extent still are, located in rural areas typified by their low household incomes but ignoring other key criteria such as water supply, soil type, topography, access to markets, feed and seed supplies. Very limited development or sustainability has been a frequent outcome.

Both traditional and more recent aquaculture development has tended to occur naturally as concentrated enterprise clusters (Porter, 2001; Little, Nietes-Satapornvanit and Barman, 2007; Ingthamjitr, Phromtong and Little, 1998). In Asia, these were often originally linked to sources of wild juveniles, and/or associated with established research or service centres disseminating knowledge.

The endurance of such clusters of enterprises suggests the benefits of such physical association outweigh the disadvantages of proximity e.g. auto-pollution, pathogen transfer etc. In contrast to the *de facto* zoning in developed economies where aquaculture sites require licences and are subject to planning restrictions, site selection in LIFDCS has typically by-passed official planning mechanisms, where they exist. Official support and/or control is often more likely and effective at the local level; for example in the Socialist Republic of Viet Nam the relative importance of District and commune level planning explains the micro-location of much recent aquaculture. Identification of designated areas for aquaculture are not always the most appropriate; rather areas have been targeted because of their low value for alternative uses or for political reasons linked to broader agendas of decision-makers (Leschen *et al.*, 2005).

Aquaculture site selection on an individual level may reflect a range of different intended outcomes. The excavated pond integrated within a mixed farm may reflect a desire for an on-farm water resource to improve crop irrigation for example as much as a fish culture unit (e.g. Dang *et al.*, 2007) or may be perceived as the heart of a rationale approach to diversification. The potential for such development may be strongly influenced by access to markets; leading to a stronger bias towards intensification in peri-urban locations (Karim *et al.*, 2011).

Urbanisation has often been an important factor in determining the location of traditional aquaculture (Little and Bunting, 2005) but the rapid transformation of rural to urban land use characteristic of many LDCS underlies much of the current dynamics in aquaculture siting. Much of the recent expansion in catfish production in the Federal Republic of Nigeria has occurred close to urban markets rather than in rural locations. The peri-urban vs rural development of aquaculture depends on the transport and communication infrastructure within individual countries and is increasingly facilitated by the use of mobile phone technology. Ha Noi, the capital of the Socialist Republic of Viet Nam, had well defined and managed peri-urban production of both fish and aquatic plants within 4 km of the city centre until very recently (Edwards, 2010), based largely on urban waste wastewater. With recent rapid urban population growth and spiralling urban land values, these urban production sites have steadily declined. Increasingly Ha Noi's growing population is supplied with farmed fish from neighbouring Hai Duong and Ha Tay provinces, with good arterial road links to the capital. In the 1990s with the arrival of "Doi Moi" and the opening up of the economy the Vietnamese government identified these provinces as having the water, land and human resources necessary for developing pond based culture and have since offered support in terms of tax concessions on equipment and inputs, and also the provision of commercial feed and fingerling supplies (Leschen *et al.*, 2005).

The concept of zoning, the purposeful inducement or coercion on the part of Government to ensure development occurs in a certain designated location has its roots in industrial development and is quite contrary to aquaculture emerging as part of an integrated local food production landscape. Such an approach places aquaculture firmly in the realm of technical and research-centric development and towards an industrial, commercial (often export) orientation. It is based on the premise that aquaculture should be supported and isolated from other activities to ensure higher standards, greater efficiencies and reduced externalities (affecting and effected by aquaculture). For example systems can be designed and planned to ensure neutral environmental impacts, rather than having to be problematically and expensively 'retrofitted' later. The concept of science parks within Universities resulting in research spin-outs into mainstream society are long established and it appears that the 'aquaculture parks' concept are following a similar path; the example of NELHA in Hawaii, the home of High Health SPF shrimp, is one example of how such a location can support development at the premium end of the value chain. This may be rather atypical in terms of high tech clustering in a production sector where competition is usually more price/scale than innovation driven (Bostock *et al.*, 2009), a characteristic that also accelerates consolidation trends.

Location with favourable access to high quality water resources is critical. Thus, plans in the Federative Republic of Brazil to implement aquaculture parks around eight reservoirs of the Paranapenema river (Murias, 2010) may on the one hand allow control of environmental impacts *from* aquaculture as well as isolating aquaculture from potential pollutants common in mixed use resources. Conceptually a large part of the value chain can be co-located in the same proximity i.e. hatchery, feed mill, grow-out and processing to reduce costs, enhance traceability and by some measures,

quality. Another example is the emergence of federal state funded "Fish Farming Estates" in peri-urban locations in the Federal Republic of Nigeria where local young entrepreneurs are provided access to key on site services such as water, electricity, drainage, markets access etc to develop concrete tank or pond culture production of the African catfish *Clarias gariepinus* (Umoro, 2012).

The implications for such zoned development on the complex social networks that develop around more conventional aquaculture development are considered later. Framing aquaculture development as a credible activity demarcated by clearly defined geographical and production limits may actually assist in gaining support for access to premium sites. The Blue Archipelago development in Malaysia (Ying, 2009) is one example of this where the case for location *within* a National Park has been negotiated on such a basis. Maintaining pristine water quality will be a requisite for retaining credibility to overseas buyers insisting on high environmental standards, as will ensure broader social benefits to employees and surrounding communities. This contrasts with many previous attempts at zoning that have attempted to exclude aquaculture from coastal areas especially those with intact mangrove areas deemed vital for their provision of environmental and related services. Many such attempts have failed and even where some level of success has been achieved there is little evidence that purposeful zoning to locate or exclude aquaculture has resulted in improved social impacts. More often development is subject to market and other forces that are difficult to manage let alone predict and plan for. A pertinent example is the "peri-urban green zones" established in Ho Chi Minh City, the Socialist Republic of Viet Nam. Although these systems continue to provide considerable employment and produce a significant proportion of the city's demand for aquatic vegetable they are increasingly under threat from urban developers who continue to encroach into such areas (PAPUSSA, 2004). Similarly the loss of city centre lakes in central Ha Noi that have important recreational, aesthetic and flood control functions in addition to being important sources of fish has required physical exclusion in some cases.

The aquaculture value chain, rather than production alone, needs to be considered within any characterisations of zoning. Thus although shrimp farming now occurs along the coastline in the Kingdom of Thailand, the concentration of processing capacity remains in the upper Gulf of the Kingdom of Thailand, a vestige of the fishery infrastructure and access to ports and major urban centres, in which market intelligence and often consumer demand is concentrated. The global interconnections of value chains have led to losses in processing clusters in Europe to Asian centres where skilful hand work, can be carried out more profitably.

Clearly, the location of aquaculture value chain activities is highly influenced by the people involved and meeting their diverse needs than the outcome of planners and regulators. These are now considered in the section below.

Location, location, location – the nature of the farming enterprise and defining the farm

The specific requirements of farming aquatic animals and the rapid social dynamic in which aquaculture has, and continues to develop necessitates a broad view of what the enterprise is and how it impacts those involved in production and indirectly.

Assuming adequate water supply and appropriate terrain for construction of production facilities, farmers may have many criteria for the specific location of their systems. Fish 'farms' are extremely heterogeneous and may not be 'easy to locate and identify', nor may 'local effects be easy to assess' as claimed (FAO, 2010). Also, of course, the term 'fish farm' does not adequately encompass most definitions of aquaculture. Edible aquatic plants of different types, for example, have distinct and specific criteria for siting. Aquaculture can be practiced either as a specialized enterprise

or one integrated with a range of other activities. Full life cycle production may occur on single or multiple sites under a large range of ownership and access arrangements. Producers may live on the farm, for part or all of the year and culture cycles may be year-round or intermittent in view of resource availability or other livelihood priorities. Site selection may be more related to access to alternate employment or markets than predictable water supply or soil retention characteristics of soils.

Water may only be seasonally or ephemerally available and production units can be sited to optimize capture of rainfall, run-off or its retention into the low rainfall months. Aquaculture can be located within watersheds in which upstream and downstream control of water and nutrient flows is limited or it may be dependent on limited groundwater or intermittent supply from centralised storage. With the advent and advance of recirculation technologies more self- contained aquaculture production can be located fairly independently of water supplies in, or on the outskirts of, urban and other water limited contexts. Such systems have the potential, usually at significant energy cost, to use water very efficiently (Verdegem, Bosma and Verreth, 2006). Aquaculture may also be a minor component of a mixed food production system, occurring within, or proximal to other crops and often with porous boundaries. Fish production within or close to ricefields or horticulture treated with pesticides is an example of a potential conflict. Ponds located downstream within watersheds may lose stock through upstream migration into a neighbour's system and/or mortalities associated with contaminated irrigation drainage from neighbours upstream. Producers may be only a small minority of households within the community but aquaculture can impact on a much broader cross-section in diverse ways. Households downstream from catfish farms in the Mekong Delta for example have been forced to source alternative drinking water following pollution events (Quach, 2008). Employment in upstream and downstream activities within aquaculture value chains can support more poor livelihoods than through farming directly (Belton, Haque and Little, 2011).

Location of aquaculture may itself be associated with social and economic status. Poorer people are typically located in more marginal agricultural land with poorer soils and water availability; status within a community may be critical for access to waterbodies. Although adoption of, and benefits from, aquaculture has often been linked to the more resource endowed section of rural communities, in some contexts the poor are more likely to be interested. In Northwest Province, Sri Lanka most potential for aquaculture was identified for poor but cohesive groups at the top of watersheds because of its better 'fit' to their livelihoods, resources and aspirations (Murray, 2004). In areas with weak law enforcement, locations that are observable and more defendable from poaching may be given priority. Clearly for many that adopt aquaculture, financial benefits are not the principle or only benefits. In one recent study, poor rice growers in the People's Republic of Bangladesh adopted the breeding and nursing of tilapia in their irrigated ricefields because in so doing they reduced their use of pesticides and increased their harvests of non-stocked fish they could harvest (Haque *et al.*, 2010). Interestingly, establishing the practice in a community tended to reduce use of pesticide overall, even among households not stocking fish (Biswas, 2008). This suggests that aquaculture can stimulate unanticipated change where it is introduced and that governance can occur at many levels as households and communities adapt and change in response to challenges and opportunities. Even where lack of governance and rapid spread of commercial aquaculture has resulted in undoubted short –term damage to the social and environmental fabric of communities, longer term adaptation and sustained benefits are possible. Belton and Little (2008) describe the complex benefits of the shrimp boom in Central Thailand where longer term benefits have been realized through the adaptive response it has triggered in communities and institutions. Also instructive in the case of Thai shrimp has been the resilience that relatively small-holder producers have demonstrated with a range

of corporate and government support. The sustained production of shrimp in the Kingdom of Thailand on relatively small but intensively managed holdings has been possible through a shift to SPF broodstock, more biosecure practices and supportive governance (Lebel *et al.*, 2010). In contrast corporate approaches to shrimp production based on large farms and employed labour have often had a poorer track record; the critical need for motivated and timely husbandry favours the continuance of self-employed labour organization, often manifested as the family farm albeit with stronger upstream and downstream linkages. These trends suggest the continuance of clustered, independently managed enterprises and the challenge of ensuring traceability and more sustainable practices. Vandergeest (2007) chronicles how local government and communities can be more effective at enhancing sustainability than externally imposed certification schemes.

Once established as an important source of foreign revenue, support from Government for the aquaculture sector may be more forthcoming. Various forms of support such as preferential duties on imported feed ingredients, favourable credit arrangements, improved infrastructure and information availability (or incentives for private provision) are examples. Net demand for raw material exports by processors and consumers in developed countries is very high; hence tariff-structures generally reflect low long-term resistance to such interventionism, particularly compared to agricultural sectors.

Global implications

The nature of global value chains in aquaculture products suggests that site selection criteria for aquaculture requires a global perspective. The concentrations of feed ingredient production from fishmeal and oil in South America and soybean in the Americas provides employment far from their use as feeds and in turn, production of tilapia and pangasius in Asia offers value addition and employment opportunities closer to their site of consumption. The trends to privatise and add value to genetic resources well established in livestock, is building momentum for farmed aquatic species as the success of SPF shrimp in Hawaii to support the Asian shrimp industry demonstrates.

Location myths

The textbook approach to aquaculture site selection has often been challenged by the reality and typically this relates to the importance, indeed the dominance, of socio-economic factors. A requirement for perennial water, optimal temperature regimes and supportive government are typically identified as key criteria for success. Lack of water as a stimulus for aquaculture development can be observed on a number of levels. The emergence of an arid country (Israel) as a leader in aquaculture through the last decades of the last century reflected a strong cultural attachment to freshwater fish but also focused a need to integrate its production into its water-limited agriculture (Mires, 2000). In well watered areas of high agricultural potential the opportunity costs of land and water are often substantial and can deter investment in a new activity such as aquaculture. Although typically 'fish bowls'-concentrations of highly productive aquaculture -are situated in well watered areas, demand for cultured fish may paradoxically be higher in areas prone to limitations in, or seasonal, water availability. Gregory and Guttman (2002) found greater interest in stocking fish in areas distant from perennial water that tended to have a greater abundance of wild fish.

Optimal temperature regimes can enhance productivity particularly in stenothermal species but there are some surprising success stories for species located well outside their native range. Production of tilapias in Maoming District, Guangdung Province in southern China has soared to be a major global supplier of the fish (producing an estimated 1/12 of the global crop) despite being located well outside the optimal temperature range of 28–32^0 (Zhang *et al.*, 2011). Ambient temperatures fall well below this range seasonally leading to occasional mass mortalities, a phenomenon not unlike

the occasional crashes in citrus and coffee in Florida and southern Brazil respectively that carry similar types of risk but remain viable and important centres for production of these crops. The other positive factors make up for the occasional mortality and in the case of tilapia, a reduced growing season even in normal years. The success in mainland China was pre-dated by previous advances in Taiwan where approaches to successfully raising tilapias on the edge of the climatic tolerance were developed. These involved modest but important technical modifications such as the use of more temperature tolerant strains (*O.niloticus* X *O. aureus* hybrid) and various overwintering techniques for different life stages. Research in Northern Vietnam, which shares a similar temperature regime, indicated that pond siting and construction in relation to prevailing winds, or use of wind breaks and, deep ponds and/or polytunnels were sufficient to cost effectively maintaining water temperatures above critical levels and ensuring juvenile fish were of a suitable size to survive overwintering (Dan and Little, 2000). Geographical separation of hatchery and grow-out has also occurred;- tilapia seed from optimal hatchery environments further south are now routinely airfreighted to the north at the onset of the growing season. In an African context the Arab Republic of Egypt, by far the continent's largest aquaculture producer, sees growth being restricted to 8–9 months of the year when ambient temperatures are close to optimal for tilapia production. The use of mitigating technical and management practices allow production and sales of 300 000 MT of tilapia throughout 12 months of the year into domestic markets (Radwan, 2011, forthcoming).

Although there are many examples of Governments being supportive of aquaculture development in countries where aquaculture has shown rapid progress e.g. the Kingdom of Thailand and the Socialist Republic of Viet Nam, there are others where progress has occurred despite a prevailing inertia or even antagonism. The antipathy towards tilapias in the Republic of India and the State of West Bengal in particular has not prevented it becoming the most important single species produced in the Kolkatta wetlands for example. Elsewhere frustration with over complex or environmentally stringent regulations or planning has been related to Europe's stagnating aquaculture development (e.g. Bostock *et al.*, 2009) This might also explain why the Republic of South Africa has not yet fully lived up to its considerable potential in developing aquaculture where some perceive over strict environmental legislation, particularly in the fish farm planning stages, has greatly reduced the opportunity for investors and individual entrepreneurs to get on the first rung of the aquaculture ladder. In reality such factors cannot be entirely delinked from many other prevailing factors including a low competitiveness compared to imports from warmer climes and high opportunity costs of location in coastal areas valued for tourism and other uses.

Gaps in the ecosystem approach to aquaculture (EAA) from a social and economic perspective

Identifying gaps in the ecosystem approach to aquaculture as a strategy from a social and economic perspective requires reflection of the process as much as the activities themselves. The following contributions demonstrate how continued effort is required to try and ensure this process contains enough self-critical reflexivity.

Participatory approaches

The purpose and intent to incorporate participatory approaches into EAA are positive but careful consideration must be given to who is encouraged and supported to participate, in what ways and for what specific purpose. Since participation has become an accepted orthodoxy in development circles and attracted both mainstreaming and inevitable criticism (see Henkel and Stirrat, 2001), greater reflection is required. Increasingly so-called participation is part of a box-ticking exercise within more blueprint approaches to development familiar in the past. Community stakeholder

engagement is frequently cursory, unrepresentative of marginal voices and more consultative than collegiate. Often, expectations within 'projects' are too narrowly sectoral involving a tiny proportion of potential stakeholders in any active way. Boundary setting and identification of stakeholders have rightly been identified as key steps. The boundaries around EAA are typically set too narrowly and the resources applied too limited and/or conservatively, for what are complex *human* systems.

The separateness of socio-economic well-being and 'ability to achieve' appears to disregard the importance of informal groups and institutions existing in complex real-world settings of legal pluralism. Collective self- organization of producers has been a common response to shared needs and not always related to more formal attempts at promoting producer associations, clubs and co-operatives based on outside incentives. Externally driven organizations have often failed because of underlying weak motivations of participants and/or objectives with unclear or unrealizable expectations. The capacity to offer goods and/ or services required by, and affordable to, any group is critical. The governance of successful groups also depends on how power relations are managed internally and with external actors. Relatively few such entities have survived in Africa despite governments and donors alike promoting them. Positive examples within Africa where both governments and developmental NGOs have learnt from previous mistakes in terms of group seaweed cultivation in Tanzania (Msuya, 2010) and the development of small to mid scale commercial fish farmers in Uganda (Walakiri and Leschen, 2011). Unfortunately analyses of the performance of such groups are few and far between (Little, 2010) and there is much to learn about their developmental impacts for members and non-members alike.

Capacity to achieve should consider culture in addition to governance and institutional issue, since the former often underlie the latter and indeed can be predisposing of certain outcomes. Thus attempts, for example, to promote cage culture among a specific marginalised group (women, an ethnic minority etc) through local NGOs should assess the likely role of such actors in effecting sustained change and incorporate mechanisms to deal with strong cultural norms on the likely long term outcomes of such initiatives. Efforts to initiate EAA should also be subject to assessment of cost benefit analysis. Given limiting resources, does the EAA promoted offer better livelihood outcomes than alternative forms of diversification, for example? Is the improved management of local fisheries a more equitable approach to supplying fish to those most dependent? Are aquatic animals from EAA the optimal source of animal source products to support local food security or should efforts be made to support alternatives such small livestock, dairying etc.

Setting boundaries for 'sustainable carrying capacities' should reflect the emerging and dynamic social relationships that surround them. Thus, the extent to which Integrated multi-trophic aquaculture (IMTA and integrated practices more generally occur within the same enterprise and are managed by the same people or between different enterprises and different people can be critical; the example of the pond operator who leases the pond bank to another for vegetable cropping is an example of this. Integration can be an outcome of both passive or active cooperation; the aquatic vegetable grower in Ho Chi Minh City, for example, who crops water spinach growing on wastewater channels in contrast to the catfish farmer who directs wastewater into a neighbour's carp pond or rice field. This latter example also demonstrates the linkages between aquaculture and other human activities both of which can be embraced by the concept of integrated farming (Edwards, 1998). Such examples also suggest the importance of reviewing aquaculture location issues in temporal as well as spatial terms. Aquatic vegetable production in Boeung Cheng Ek, Phnom Penh and the Kingdom of Cambodia is highly seasonal in terms of employment, drawing migrant labour from rural areas outside of the main rice growing seasons and highlighting the strong rural: urban linkages that characterise such activities. The outputs moreover

are particularly important to poorer consumers (PAPUSSA, 2004) and the system provides an environmental service i.e. an effective biological treatment of 80 percent of the city's urban waste water – that benefits a much larger group of stakeholders that remain unaware of its role in sanitation and support to public health. Such systems together with the development of IMTA involving co-location of caged finfish, bivalves and seaweeds share a need to assess social and economic benefits across the value chain and social spectrum of stakeholders impacted. There is a need for quality, quantity and time (QQT) attributes to be incorporated into indicators of EAA impact that reach well beyond the farm and the direct producer and these are now considered.

Indicators

The development and use of indicators should ideally be based on a synthesis of top down 'expert' and local 'bottom-up' opinion (Bell and Morse, 2008). Indicators should enable a robust baseline of impacts to be built and be a solid basis for further understanding change over time. While site specific, some indicators are more generic and should also allow some comparison between sites and systems.

Indicators within the broader producer community should be ideally monitored over time and/ or matched with otherwise similar communities without aquaculture established as a major activity. These activities would point to the depth and spread of impacts within communities in which aquaculture is established, either through direct participation as producers or indirect or secondary benefits through employment or linkages within the economy. Beyond the net benefits, they also indicate if once established aquaculture supports or detracts from equity within the community.

- Proportion of households within the community that gain some benefit(s) from aquaculture during the year-evidence for complementarity within the livelihood portfolio
- Trend of increasing median incomes of all households in the community where aquaculture is practiced
- Low SE of the mean for monthly household incomes in aquaculture communities
- Increasing trend in day labour rate (both in aquaculture and non-aquaculture related activities (Faruque, 2007).

Indicators for households accessing and managing aquatic systems would aim to assess the proportion of households that benefit as producers (how equitable or polarized production is) and how resilient the systems are in terms of ecology and social economics. The prevalence and rationale for polyculture at production unit and/or community level is an indicator of both ecological and economic resilience and, because it results in different levels of by-products being generated, likely high benefits for poorer people as employees and consumers. Similarly evidence for water and nutrient-reuse locally is likely to be a useful indicator of resilience. Switching of species indicates again a capacity for change in the face of adverse economic and/environmental shocks (such as small-scale farmers in the Mekong Delta changing from pangasius to other species; Loc *et al.*, 2010). The proportion of farming households that invest in significant stock protection, the level and means of which needs to be locally contextualized, could signal the level of on-going social conflict related to aquaculture development. Many of these indicators are evidence for adaptive learning at the household and community level.

- Proportion of households within the community attempting some aspects of aquaculture-stocking of seed –indicative of impending need for food security or overcoming temporal shortages (seasonal and/or year on year)
- Producer households demonstrating some form of adaptive management of their managed aquatic system to mitigate flood/drought risks
- Number of benefits expressed by households from adoption of aquaculture (Haque *et al.*, 2010). A large number of benefits perceived by a high proportion of adopters suggest that adoption brings a range of benefits many of which are non-financial

- Number of households with units of production, and low SE of the mean number of units per household
- High species variability within culture systems either as concurrent or rotational polycultures at household and community level
- Variation from average model traced to initial adoption by pioneers
- Evidence for wholesale switching species in response to market signals
- Evidence for water/nutrient reuse from aquaculture systems and values attained for such initiatives (social, nutritional and/or financial)
- Proportion of producers that invest significantly in stock protection and/or lose a significant amount of stock to poaching, predation and/or poison
- Proportion of producer enterprises based on outside investment

Indicators for producer associations/groups/clubs which are increasingly recognized as critical assets to support common action and social learning but for which governance and inclusion are issues

- Trends in exclusions from and conflicts within producer associations
- Evidence for sustainable rules, transfers of responsibilities, transparent procedures
- Independence from outsiders and subsidies
- Demonstrated participation by women, minorities and normally marginalized groups

Indicators for poverty impact of aquaculture

- Decline in relative price of fish over last five years
- Proportion of fish sold in the community sourced from local aquaculture as an indicator of multiplier effects
- Evidence for increase in number of meals including fish increasing among the poorest groups in the community since aquaculture established
- If irrigation function of ponds support horticulture evidence for greater, more consistent consumption among poor groups of fresh vegetables derived from such systems
- Do we see a decline in equity over time after introduction/establishment of aquaculture in a given context (*Aquaculture-related Gini index*?)
- Evidence for increases in number and density of activity nodes within 'actor networks'; trends towards spread from immediate kin to distant and non-relatives (specific to cultural context)
- Evidence (longer term) for aquaculture supporting escape from poverty and/or preventing decline into poverty (Krishna,2007; Belton, Haque and Little 2012)
- Intergenerational welfare indicators

Summary

The location of aquaculture activities has historically been based on a combination on local demand and agro-ecology, with global demand and deteriorating capture fishery stocks having an increasing influence. External interventions aimed at stimulating aquaculture in developing countries have often been driven by objectives and geographical boundaries without paying enough attention to other key criteria for successful aquaculture, often resulting in limited development and sustainability. Meanwhile, established and developing aquaculture sectors have been seen to 'cluster' around important resources or services, to greater effect. Site selection in un-planned clusters is based on factors beyond basic resources and services required; proximity to markets is a key driver for peri-urban production for example. Transport links are important in creating options and greater production efficiencies in commercial farms. Aquaculture has been seen to flourish away from ideal production environments, such as in Israel where water resources are scarce, and tilapia production in the People's Republic of China where water temperatures are well outside the optimal range. Attempts to restrict certain types of aquaculture or limit them within zones have often failed, especially in countries with weak governance. Factors specific to local natural,

social and economic environments can be major drivers in aquaculture. Aquaculture has potential to exert significant social and economic impacts through upstream and downstream links around the use of chemicals, wastes expelled and stock migration. This incorporates a broad section of people as stakeholders in the broader system. Similarly, employment along the value chains, both upstream and downstream, bring benefits to many not involved in farming directly.

Focus in development programs should be placed on identifying and responding to local factors, rather than allowing top-down, external factors to dominate. Community stakeholder engagement needs to be strengthened, with more rigorous application of cost benefit analysis. Alongside immediate economic concerns, a broad understanding of the social and ecosystem services that are part of aquaculture and associated value chains must be considered. Identification and use of appropriate indicators can be a robust approach to assessing impacts, and must pay equal attention to local conditions and opinion if they are to be accurate and relevant in their application.

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Legal and policy components of the application of the ecosystem approach to aquaculture to site selection and carrying capacity

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Abstract

The sustainable development of aquaculture largely depends on the right selection of the site and the correct determination of the amount of biomass that can be supported by the ecosystem. In order to establish these aspects, the strategy of the Principles of EAA, held by FAO Expert workshop: Building an ecosystem approach to aquaculture, in Palma de Mallorca 2007, should be a guide for policy-makers. Legally speaking, all these principles are considered in the principles of international environmental law. Nevertheless, regulation varies among states. Different levels of authorities, policy-making processes and regulatory mechanisms are aspects that reflect different levels of application of the EAA principles, and therefore, different degrees of compromise with the aquaculture sustainability. This paper outlines the legal difficulties for the application of the principles of EAA for the aquaculture site selection and carrying capacity. For these purposes, the review is focused on the influence of each principle of EAA, from the principles of international environmental law perspective. The work includes a description of the requirements that legal and institutional frameworks should implement, in order to ensure a correct application of the Principles of EAA to the aquaculture site selection and carrying capacity.

Introduction

Site selection is one of the major concerns in aquaculture. The right selection of a site has influence not only in the potential of the activity but also in the social and economical sustainability. Besides siting, carrying capacity of environment is considered a requirement for an ecologically feasible aquaculture. Both requirements will be discussed in this review from the perspective of the ecosystem approach to aquaculture.

The three key principles to guide the ecosystem approach to aquaculture (EAA), agreed during the FAO Expert workshop in 2007 are[1]:

- Principle 1: "Aquaculture development and management should take account of the full range of ecosystem functions and services, and should not threaten the sustained delivery of these to society."
- Principle 2: "Aquaculture should improve human well-being and equity for all relevant stakeholders."
- Principle 3: "Aquaculture should be developed in the context of other sectors, policies and goals."

From a legal perspective, all these principles, and particularly the first one, are considered in the principles of international environmental law. These principles are sovereignty over natural resources; responsibility not to cause damage to the environment of other states or to areas beyond national jurisdiction; principle of preventive action; precautionary principle; responsibility or polluter pays principle; cooperation principle; sustainable development; principle of common but differentiated responsibility, among others.[2]

Since principles in international environmental law are binding, they are expected to be followed up by states. Nonetheless, international environmental principles must always have their limitations in so far as they are drafted remotely from the actual circumstances and activities.[3] Moreover, its implementation and law enforcement vary among countries. Therefore, legally speaking, the EAA principles could be reinterpreted by each nation. These reinterpretations explain the significant differences in the regulation of aquaculture site selection and carrying capacity from nation to nation. This review is focused on how the EAA principles have an influence in site selection and carrying capacity, and which considerations and recommendations could be considered by countries when aquaculture should be regulated.

Principle 1: "Aquaculture development and management should take account of the full range of ecosystem functions and services, and should not threaten the sustained delivery of these to society"

As mentioned above, all the EAA principles are included in the principles of international environmental and sustainability law, but particularly the first one.[4] Thus, it is reasonable to begin our analysis with the application of this principle to the aquaculture site selection and carrying capacity. This principle may be considered as a

[1] Soto, D., Aguilar-Manjarrez, J. & Hishamunda, N. eds. 2008. *Building an ecosystem approach to aquaculture*. FAO/Universitat de les Illes Balears Expert Workshop. 7–11 May 2007, Palma de Mallorca, Spain. FAO Fisheries and Aquaculture Proceedings. No. 14. Rome, FAO. 2008. 221 pp. (also available at www.fao.org/docrep/011/i0339e/i0339e00.htm).

[2] These principles are United Nations principles and have been incorporated into four catalogues, with two types of texts: "political text approved by high level representatives (heads of state and government or ministers)" –Stockholm Declaration, Rio Declaration– or text (...) emanating from selected bodies of lawyers and environmentalists [United Nations Environmental Programme and Commission on Sustainable Development], bodies which reflect nevertheless to a large extent the views of governments in spite of certains affirmations to the country". Lang, Winfriend, UN Principles and International Environmental Law, Max Planck yearbook of United Nations law (editors: Jochen Frowein and Rüdiger Wolfrum) (First Edition, Kluwer Law International, Great Britain, 1999), pp. 164.

[3] Howarth, W. 2006. Global Challenges in aquaculture regulation, In D.VanderZwaag and G. Chao (eds). Aquaculture Law and Policy: towards principled access and operation. Routledge Tayler & Francis Group, London and New York. pp. 18.

[4] Bermúdez, J. 2008. Legal implications of an ecosystem approach to aquaculture. *In* D. Soto, J. Aguilar-Manjarrez and N. Hishamunda, eds. *Building an ecosystem approach to aquaculture*. FAO/Universitat de les Illes Balears Expert Workshop. 7–11 May 2007, Palma de Mallorca, Spain. FAO Fisheries and Aquaculture Proceedings. No. 14. Rome, FAO. pp. 67–78. (also available at www.fao.org/docrep/011/i0339e/i0339e00.htm).

holistic or *ecological* approach, considering its ability to deliver functions and services from the environment, as a whole, to society. A holistic or ecological approach has specific implications when it considers carrying capacity and site selection.

1. Carrying capacity

Environmental carrying capacity is defined as "the maximum number of animals or amount of biomass that can be supported by a given ecosystem for a given period of time.[5] If we want to assess the suitability of a site for aquaculture, we need to predict potential future impacts of the planned activity".[6] The key issue of this principle is to estimate limits to "acceptable environmental change".[7] In the consideration of this issue it is important to keep in mind that the national regulation of aquaculture site selection must consider carrying capacity as a *logic step* in order to establish a sustainable legal framework for the activity. However, regulation of aquaculture varies among states and currently only a few countries apply a carrying capacity.[8] Nevertheless, most countries use some form of environmental quality standards (for instance, based on fixed levels of nutrient inputs or amount of chemicals).[9]

Environmental quality standards set concentrations in the environment for certain compounds, below which unacceptable effects are expected not to occur.[10] One problem of setting standards is that not all of them are legally enforceable. Many of them are fixed in guidelines that usually embody political commitments, rather than legally binding obligations.[11] Moreover, since the establishment of these standards implies that something is defined by policy-makers rather than by scientists, it is important to ensure harmonization and reduce the arbitrariness of the authority.[12] Here comes the idea of a compromise among the different interests and stakeholders, which are implied in the application of a standard. The ability to ensure carrying capacity could not be reach only with environmental or scientific requirements but also with social and political acceptance. In this point the application of soft law instruments must be considered as an important element of harmonization of legally enforceable standards.

2. Site selection

Success or failure of any aquaculture venture largely depends on the right selection of the site for it.[13] Site selection is the process of selecting a certain space in the marine environment by examining environmental, technical, legal, administrative, social, economic and other related aspects, in order to set up an aquaculture project.[14] Several factors are to be considered. The processes of site selection include scientific knowledge, tools and legal frameworks, as well as tools for decision-making and management.[15] Therefore, policy-makers must examine a wide range of disciplines, from socio-economic aspects to environmental conditions.[16]

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[5] IUCN. 2009. Aquaculture Site Selection and Site Management, IUCN, Spain, pp. 201.
[6] Ibid, pp. 204.
[7] Costa-Pierce, B. 2010. Sustainable Ecological Aquaculture Systems: The Need for a New Social Contract for Aquaculture Development. Marine Technology Society Journal, 44 (3), pp. 92.
[8] Holmer, M., Hansen, P.K., Karakassis, I., Borg J.A. & Schembri, P.J. 2008. Monitoring of environmental impacts of Marine Aquaculture. In: Holmer M., Black K., Duarte C.M., Marba N., Karakassis, eds. *Aquaculture in the Ecosystem*. Springer, pp 47–85.
[9] Ibid, pp. 48.
[10] IUCN, cit. (No 4), pp. 202.
[11] Ibid, pp. 202.
[12] Ibid, pp. 202.
[13] FAO. 1987. Site Selection For Aquaculture: Aquatic pollution. Text by Kutty, M. In FAO Fisheries and Aquaculture Department [online]. Nigeria. www.fao.org/docrep/field/003/AC178E/AC178E00.htm
[14] IUCN, cit. (No 4), pp. 266.
[15] Simard, Ojeda and Haroun. 2008. The sustainable development of Mediterranean aquaculture: Problems and perspectives. Options Méditerranéennes, 62, pp. 120.
[16] FAO, cit. (No 12).

These have made the sitting choice the most controversial regulatory decisions in salmon aquaculture[17], and this dilemma can be said for almost all culture types.

Currently, most countries have specific demands for the locations of the farms to avoid situating these near habitats of special interest (recreation, wildlife, fishing zones) and near industries and sewage outfall.[18] Nonetheless, the correct aquaculture site selection implies to consider a *logic step*: estimate the carrying capacity of the site. In some cases, this factor allows establishment of different categories of sites. For instance: a) where fish farm will only be acceptable in "exceptional circumstances"; b) where areas are at the limits of their carrying capacity; and c) where there is a better prospect of satisfying nutrient loading and benthic impacts.[19]

In summary, only those areas in third category are likely to be acceptable for new fish farm development.[20] Nevertheless and as noted above, only a few countries apply a carrying capacity at the moment. Hence, regulators usually have few or no adequate procedures to establish such categories of sites. On a regional and international level, there is another problem. In many cases, siting decisions are made in response to singular applications. This is the *site-by-site* regulatory mechanism. This regulation – reactive, rather than proactive– ignores that many of the major concerns of aquaculture involve regional or cumulative impacts.[21] The Environmental Impact Assessment could be a useful tool to solve this problem. However, in most cases it is carried out after the site is selected, so there is not currently a tool for site selection, but rather for the monitoring of the environment in regard to aquaculture development.[22]

Recommendations

Countries should implement aquaculture carrying capacity, which implies more than emission or environmental quality standard. This factor will allow to establish different categories of sites and to identify those areas that are likely to be acceptable for aquaculture development. Since there is no consensus among stakeholders and countries in order to set acceptable ecological aquaculture impacts, it is important to ensure a harmonic regulation. There are different mechanisms. One of them is to define acceptable impacts by establishing criteria and variables to be used for estimating carrying capacity.[23] Another tool is the use of variables related to environmental quality or standards –for instance: primary production and sediment oxygen levels–.[24] In any case, the application of soft law instruments must be considered as an important element of environmental standards harmonization.

[17] McDaniels, Dowlatabadi, H. & Stevens. 2005. Multiple scales and regulatory gaps in environmental change: the case of salmon aquaculture. Global Environmental Change, 15 (1), pp. 17.

[18] Holmer *et al.*, cit. (No 7), pp. 48.

[19] Howarth, cit. (No 2), pp. 24.

[20] Ibid, pp. 24.

[21] McDaniels *et al.,* cit. (No 16), pp. 17: "With site-by-site regulation it is difficult to address cumulative impacts, which underlie almost every significant environmental debate and has been widely recognized as a significant barrier to sound environmental management (Burris and Canter, 1997; Canter and Kamath, 1995; Orians, 1995; Smit and Spaling, 1995). In this case the inattention to cumulative impacts seems to have led to significant confusion over how to manage salmon aquaculture in the province. Regulators and policy-makers are unsure what cumulative impacts if any, fish farms will have on wild salmon stocks, other marine species, economic development, or even human health (Ellis, 1996; Leggatt, 2001; Pacific Fisheries Resource Conservation Council, 2002)."

[22] Simard *et al.*, cit. (No 14), pp. 120.

[23] IUCN, cit. (No 4), pp. 202: "some of the most difficult issues that need to be considered include: The ecological component of carrying capacity that is to say, what are unacceptable ecological impacts? A series of environmental variables like low oxygen in the water (hypoxia), high chlorophyll a or particulate organic carbon (eutrophication), as well as damage to important habitats or species may be chosen. One example is the use of 'exclusion criteria' such as protected habitats or species, for example *Posidonia oceanica* meadows (distance > 800m) or maerl beds, as well as activities that could be harmful for aquaculture by causing harmful algal blooms (HABs) or polluted sites".

[24] Ibid., pp. 203.

Finally, it is important to overcome the *site-by-site* regulation process. Decisions on site selection are made on an individual basis in response to applications for tenure.[25] This mechanism ignores that many of the major concerns involve regional or cumulative impacts.[26] The question about size and distribution of aquaculture activity can neither be answered by considering local, site-by-site criteria, nor by a process that is reactive rather than proactive.[27] The problem of siting criteria has to be dealt with in a region-wide planning, through appropriate regulations aimed to address cumulative impacts.[28]

Principle 2: "Aquaculture should improve human well-being and equity for all relevant stakeholders"

Aquaculture is a human activity, in this sense it should tend to human well-being, considering the wide range of people who are benefited or affected by it. This second EAA principle could be summarize in the aim of equity in aquaculture, which should be recognized in site selection and carrying capacity.

1. Site selection

After understanding the interaction between aquaculture and the environment, site selection is the next step towards an ecosystem approach to aquaculture. However, it includes social and economic development requirement as well.[29] According to the definition of sustainable development, a sustainable aquaculture should be *environmentally acceptable*, *economically viable*, and *socially equitable*.[30] The principle under analysis is focused on these last two components. There are many persons and groups who have interest in aquaculture, as well as those who are interested because they live near to aquaculture sites.[31] Aquaculture should provide *well–being* and *equity* for all these relevant stakeholders, especially at local level, so it does not bring detriment to any sector of society.[32] In this context, site selection is related with equity, or more accurately, is related with environmental justice. Clear legislation is key in this point. It must reflect these social and economic issues. For example, a legislation which strongly promotes aquaculture activities, could decrease prices of products from fisheries, and cause poverty among fishermen. Therefore, a legal framework that does not consider these aspects could cause a lack of legitimacy of the activity.

To integrate these components is not easy. If the rules of site selection are too strict, they could lead to a relocation of aquaculture facilities from one country to another one with less or no legal restrictions. This situation provides an easy way if not an excuse to run away from regulation. In this scenario, the benefits of aquaculture will not be *widely spread.* This implies an environmental justice problem that affects countries –and specifically, people who live near the sites– where aquaculture site selection have less or no restriction at all.

2. Carrying capacity

In the pursuit of improving human well-being and equity, several factors are to be considered, not only the ecological ones, but those related to human health and food

[25] McDaniels *et al.*, cit. (No 16), pp. 17.
[26] Ibid., pp. 17.
[27] Ibid., pp. 17.
[28] Ibid., pp. 18.
[29] Simard, F. *et al.*, cit. (No 14), pp. 119.
[30] Ibid, pp. 113.
[31] Mazur and Curtis. 2008. Understanding community perceptions of aquaculture: lessons from Australia. Aquaculture International, 16 (6), pp. 604.
[32] Costa-Pierce, B., cit. (No 6), pp. 93.

safety. In this context, it is evident that aquaculture carrying capacity is an important aspect in order to maintain an activity without health and environmental risks. Aquaculture water use and pollution can have damaging impacts on ecosystems, in particular in areas with low carrying capacity or where the carrying capacity has already been reached.[33] Regulatory authorities are interested in minimizing these negatives environmental impacts through different mechanisms. The problem is that regulators and policy-makers usually are unsure of what impacts –and mainly cumulative impacts– aquaculture will have on marine species, economic development, or even human health.[34] Extensive investigation is necessary in order to determine when a risk is capable of being converted into a harm. Where research of this kind has not been undertaken, legislation may be justified on preventive or precautionary principle.[35]

Another problem is the cost of the environmental protection. It is accepted that the costs of the fight against pollution should be borne by the polluter. This implies the application of the polluter pays principle (PPP) to the aquaculture activity. The polluter-pays principle is an economic principle. Applied to the field of aquaculture, this means an imposition of the cost of aquaculture pollution abatement on individual polluters, rather than on the public purse, to be passed on the consumer, and thus in the end reflected in the price of the product.[36] However polluter pays principle implies an obligation that is not easy to measure, neither to assign. In several cases PPP leads to bankruptcy or even to an illegal activity.

Recommendations

Aquaculture legal framework must allow to provide substantial benefits to mankind. It must also ensure environmental and social standards. Inevitably, this implies to define the boundary between permissible and impermissible activities. Every site selection process must provide a minimum standard for each individual siting decision, in order to ensure not to cause detriment to any sector of society. Arguments that justify adverse environmental impacts in developing countries, where the threat of poverty and starvation provides a justification, should be considered with caution.[37] This implies an environmental justice problem that can lead to a relocation of the activity in countries with no legal restriction or where restrictions are less strict. The principle under study implies that this argument is never acceptable in developed countries, where environmental expectations should be stricter.[38]

From the carrying capacity perspective, the key issue here is to estimate the resilience capacity or the limits of acceptable environmental change. The problem is that regulators and policy-makers are not certain about cumulative impacts, if any, aquaculture will have.[39] One could visualize a potential role of local, informal, traditional knowledge regarding potential carrying capacities and impacts. This kind of knowledge may be highly useful into the regulatory process.[40]

Finally, the ecological approach to aquaculture –and the improvement of human well-being and equity for all relevant stakeholders– must always consider two principles of the international environmental and sustainability law: the precautionary principle or approach and the polluter-pays principle. The first provides action to

[33] IUCN. Shrimp Aquaculture: High value for whom? 2008. IUCN, Holland, pp. 2
[34] McDaniels, T. *et al.*, cit. (No 16), pp. 18.
[35] Howarth, W., cit. (No 2), pp. 20.
[36] For a review of the polluter pays principle, see: Louise Larsson, M. 1999. The law of environmental damage: liability and reparation. Kluwer Law International, Sweden. pp. 90.
[37] Howarth, W., cit. (No 2), pp. 19.
[38] Ibid., pp. 19.
[39] McDaniels, T. *et al.*, cit. (No 16), pp. 18.
[40] Ibid., pp. 18.

avoid serious or irreversible environmental damages before a scientific certainty of harm could be achieved.[41] On the other hand, the principle of polluter-pays is the basis of environmental management for the cost of environmental damage as well as its monitoring and rectification.[42] The implementation of this principle –through licensing systems– can offer an important incentive for reducing aquaculture pollution.[43]

Principle 3: "Aquaculture should be developed in the context of other sectors, policies and goals"

This principle could be interpreted as the integration or relationship of aquaculture with other activities. Since aquaculture activities should take into account the existing activities in the same area.

1. Site selection

Aquaculture has been recently developed, mostly in coastal areas. In these areas a large number of activities have been done before. As well as a variety of others economic activities, tourism is among them. Therefore, aquaculture is a newcomer, which has destroyed the *status quo* established by existing users.[44] Government priorities based on reasons of wealth and employment usually, make this competition for space a problem even more difficult to solve.[45]

The conflict and overexploitation of stocks in fisheries have long consisted in expansion of fishing areas. The evolution of the fisheries shows a way to solve a problem that is not necessarily sustainable. In the case of aquaculture the problem of space has to be deal in a manner that has to be comprehensive, sustainable and ordered. Therefore the relocation of coastal aquaculture sites to new areas offshore should not be seen as the only solution. One aspect is the legitimacy of the activity. Policy-makers have generally carried forward a policy process in an old fashioned way, which meant that local population accepts the resource development and exploitation as a goal itself.[46] At present, however, more sophisticated policy-making is required: not only to promote industrial activity, but also to legitimize the process. As we have said before, acceptability of aquaculture is linked to the participation of all relevant stakeholders. [47- 48]

In a legal framework, Advisory Committees are procedural instruments, which tend to deal with this issue. They are composed of groups of people affected by the installation of the aquaculture facilities or with the determination of the appropriate area for aquaculture. These Committees could be a real vehicle for participation and legitimacy whereby the community comes to an agreement on the best way to proceed.[49] But procedural instruments are not enough. Substantive instruments that take into account the territorial integration of the activity it is necessary to have. This implies spatial specialization and control of environmental effects. The policies of

[41] IUCN, cit. (No 4), pp. 71.
[42] Kutty and Pillay. 2005. Aquaculture: principles and practices. Blackwell Publishing, India, pp. 17.
[43] Middlen and Redding. 1998. Environmental management for aquaculture. Chapman & Hall, London, pp. 203.
[44] IUCN, cit. (No 4), pp. 167.
[45] Ibid, pp. 166.
[46] Kaiser and Stead. 2002. Uncertainties and values in European aquaculture: communication, management and policy issues intimes of "changing public perceptions". Aquaculture International, 10 (6), pp. 483.
[47] Simard, F. *et al.*, cit. (No 14), pp. 113.
[48] Kaiser and Stead. cit. (No 46), pp. 484: "It is necessary to take time constraints into account, and to anticipate and deal early on with the danger of building too high expectations from participatory approaches (...) On the one hand, one needs to avoid making the process too cumbersome, or onerous, as this carries the danger of alienating some interests, loosing sight of the purpose. On the other hand, one may need some visible results in order to strengthen the stakeholders' belief in the utility of the process."
[49] Howlett and Rayner. 2004. (Not so) "Smart regulation"? Canadian shellfish aquaculture policy and the evolution of instrument choice for industrial development. Marine Policy, 28 (2), pp. 181.

Integrated Coastal Zone Management aim to achieve this purpose. They integrate a contractual logic and include the participation of other partners, through the use of consultation processes, around common goals.[50]

2. Carrying capacity

The general objective of the carrying capacity process is to provide *appropriate knowledge* to the administrative authorities and other decision-making bodies in order to plan the activity.51 This appropriate knowledge is important at a local and at a regional level, but the question of what role aquaculture should play in the international level is not answered through taking into account values and technical information in an overall decision-making process.[52] Even more, internationally speaking, at present there is not an organization with a specific mandate related to aquaculture.[53] Thus, there is no authority with the power to enact a comprehensive international regime to shape and moderate the cross-scale impacts of decisions regarding aquaculture at the national and lower levels.[54]

The above situation has an influence in the national legal and policy management of aquaculture. Therefore, the question about what role aquaculture should play in national economies is answered through the interaction of various international agreements and the institutions that administer them, as well as through the influence of national, sub-national and transnational institutions on these international regimes. [55]

Hence, authors distinguish different levels of authority, each of which must answer different questions about aquaculture activities. The institutions with regional jurisdiction have better access to region-wide information and resources to study and regulate regional impacts. They must decide about the size and distribution of the aquaculture activity in a specific region.[56] On the other hand, local level has reduced resources, information and technical expertize, even though they are legally entitled to determine local land uses. Thus, they must define where farms should be sited in the short term.[57] This level decision involves the application of siting criteria and process. The siting criteria and process are expected to reflect economical, environmental and social considerations.[58]

Recommendations

There are many people and groups who are concerned about aquaculture, especially those who are interested because they live near to aquaculture sites. The concept of *acceptability* is linked to the participation of all relevant stakeholders.[59] Therefore, policy-making should not only focus on the use of policy instruments to promote industrial activity, but also those required to legitimize the process.[60] Since we are engaged with 'socio-environmental conflicts', rather than 'social' or 'environmental' in a fragmented way,[61] the manner in which conflicts can be avoided, negotiated and resolved are key aspects of the legal framework. In some cases, the participation of the stakeholders takes place in the

[50] McDaniels, T. *et al.*, cit. (No 16), pp. 19.
[51] IUCN, cit. (No 4), pp. 167.
[52] McDaniels *et al.*, cit. (No 16), pp. 14.
[53] Bermúdez, J., cit. (No 3), pp. 70.
[54] McDaniels *et al.*, cit. (No 16), pp. 14.
[55] Ibid., pp. 14.
[56] Ibid., pp. 15.
[57] Ibid., pp. 15.
[58] Ibid., pp. 15.
[59] Simard *et al.*, cit. (No 14), pp. 113.
[60] Howlett, M. and Rayner, J., cit. (No 49), pp. 172.
[61] Barton and Floysand. 2010. The political ecology of Chilean salmon aquaculture, 1982–2010: A trajectory from economic development to global sustainability. Global Environmental Change, 20 (4), pp. 741.

environmental impact assessment process, which should consider social standards as well. In other cases, participation is led through regional aquaculture advisory committees. The strategy behind such an approach is to obtain a vehicle whereby the entrepreneur and community come to an agreement on the best way to proceed.[62] Other institutional structures are: co-management arrangements, multi-stakeholder processes, development and empowerment-oriented co-management organizations, and more widespread civic science and policy communities.[63]

From the administrative perspective, the problem is that local governments usually find themselves under significant pressure to block applications for siting of new aquaculture facilities.[64] The application of the coordination principle should avoid this conflict. This principle implies that different actors have different responsibilities. Institutions with regional jurisdiction must decide about the size and distribution of the aquaculture activity in a specific region, whereas local authorities –with reduced resources and information– must define where farms should be sited. Therefore, it is expected that the institutional or governmental structures should be compatible with the multiple level of decision required to address an environmental problem involving.[65]

Conclusions

Regulation of aquaculture site selection and carrying capacity vary among states. The analysis of the legal framework allows us to conclude the following:

1) From the environmental perspective. Carrying capacity allows to identify where aquaculture should be developed, establishing of different categories of sites. Therefore, carrying capacity should be considered as a *logic step* in order to establish a sustainable legal framework for aquaculture. Nevertheless, currently only few countries apply this parameter. From the site selection perspective, aquaculture should avoid the *site-by-site* regulatory mechanism. This regulation –reactive, rather than proactive– implies that siting decisions are made in response to singular applications and ignores that many of the major aquaculture concerns involve regional or cumulative impacts. The problem of siting criteria has to be dealt with in a region-wide planning.

2) From the improvement of human well-being and equity perspective. Several factors are to be considered in order to improve human well-being and equity. Aquaculture carrying capacity is an important aspect of them. The problem is that regulators are usually unsure of what impacts aquaculture will cause. Where research has not been undertaken, legislation may be justified on the precautionary principle. On the other hand –and in the context of improving human well-being and equity– it is accepted that the costs of the fight against aquaculture pollution should be borne by the polluter.[66] Aquaculture site selection should also aim to provide *well–being* and *equity* for all the relevant stakeholders, especially locally. But to integrate these components is not easy. In many cases, a strict regulation of site selection can lead to a relocation of the aquaculture in countries with no legal restriction, or where restrictions are less strict. This implies a problem in relation with environmental justice. Non-binding legal instruments (or so-called soft law instruments) play an important role in the solution of this problem.

[62] Howlett, M. and Rayner, J., cit. (No 49), pp. 180.
[63] McDaniels, T. *et al.*, cit. (No 16), pp. 20.
[64] Ibid., pp. 18.
[65] Ibid., pp. 20.
[66] Haylor and Bland. 2001. Integrating aquaculture into rural development in coastal and inland areas. In R.P. Subasinghe, P. Bueno, M.J. Phillips, C. Hough, S.E. McGladdery & J.R. Arthur (eds). Aquaculture in the Third Millennium. Technical Proceedings of the Conference on Aquaculture in the Third Millennium, Bangkok, Thailand, 20–25 February 2000, pp. 77.

3) From the social perspective. The objective of the carrying capacity process is to provide appropriated knowledge to the administrative authorities, in order to plan the activity. In the legal framework, it is common to find different levels of authority. Institutions with regional jurisdiction, with higher access to region-wide information and resources, must decide about the size and distribution of the aquaculture activity in a specific region. On the other hand, at local level it must be defined where the farms should be sited in the short term. From the site selection perspective, acceptability of aquaculture is linked to the participation of all relevant stakeholders. Therefore, a sophisticated policy-making is required: not only to promote industrial activity, but also to legitimize the process. Advisory Committees and Policies of Integrated Coastal Zone Management aim to achieve this purpose.

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From estimating global potential for aquaculture to selecting farm sites: perspectives on spatial approaches and trends

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Abstract

The spatial domain of carrying capacity and site selection extends from global to local, and it is suggested that estimating potential (capability for aquaculture development) and zoning (partitioning space for aquaculture) should be added to site selection and carrying capacity to make four essential tasks that are at the same time important spatial and temporal issues in aquaculture today. There is a clear trend for "all-in-one" applications that include multiple objects (species at different trophic levels and varied culture systems), incorporate multiple functions basic to aquaculture development and management (site selection, carrying capacity, monitoring for management including legal aspects), that take into account ecosystem level spatial boundaries, involve active participation or scrutiny by the public and that produce outputs that are highly relevant to managers, commercial entities and to aquaculture practitioners. There is a need to extend the temporal and spatial scale of the "all-in-one" applications so that they can be implemented early on in aquaculture development planning in a precautionary way and at national levels even with the disadvantage of less certainty in the results. The main bottlenecks to implementing broad scale spatial analyses are lack of data of appropriate resolution and variety of data needed as input to the models. In conclusion, while technical capabilities to deal comprehensively with aquaculture issues in space and time are rapidly improving, this contrasts with the apparent problem of disseminating the techniques and building the capacities to utilize them.

Introduction

The task assigned for this review was to cover key drivers and issues surrounding carrying capacity and site selection, with emphasis on global versus local modelling and with regard to the ecosystems approach to aquaculture (EAA).

Most aquaculture development and management issues, including carrying capacity and site selection, are driven by spatial considerations. Computerized spatial analyses have been used to address the "What, where, and how much?" of production activities since the early 1980's, but the EAA provides an additional impetus to use spatial analyses to expand coverage to "For whom and with what social, environmental and economic consequences?" as obligatory additional questions. Recognizing the importance of spatial considerations among the drivers of aquaculture development opens up several underlying objectives for this review:

- To characterize the role and future trends of spatial analyses to resolve aquaculture issues, to accelerate aquaculture development and to facilitate its management within the framework of the EAA; and
- To identify technical gaps and to recommend ways through which leveraging the deployment of spatial analyses could contribute more fully to aquaculture development by becoming more widespread and more effective.

Considering that the spatial domain of the assigned task extends from global to local, then estimating potential (capability for aquaculture development) and zoning (partitioning space for aquaculture) were added to site selection and carrying capacity to make four essential tasks that are at the same time important spatial and temporal issues in aquaculture today. Two recent studies provide, starting points, avenues and perspectives for this review. The first of these is on progressing aquaculture through virtual technology and decision-support tools for novel management (Ferreira *et al.*, 2012) that defines the role of spatial analyses in the realm of aquaculture development and management. The second study deals with the potential of spatial planning tools, namely GIS, remote sensing and mapping, to support the EAA (Kapetsky, Aguilar-Manjarrez and Soto, 2010). Although the insights from this study are more general in so far as they deal with the full spectrum of spatial issues in aquaculture, they do pertain well to the four issues that are the focus of this review. Estimating potential, zoning, site selection and carrying capacity are characterized in terms of where they have been employed and attention is called to example applications with special merit. Estimating potential at national levels as a first step towards planning for aquaculture development is illustrated by a recent global analysis of mariculture potential of all maritime nations (Kapetsky and Aguilar-Manjarrez, 2013). Finally, conclusions are drawn on trends in spatial analyses for aquaculture, technical and capacity gaps are highlighted and recommendations are made for future activities.

Spatial tools in aquaculture from the view point of virtual technology

Virtual Technology has been defined by Ferreira *et al.* (2012) as "any artificial representation of ecosystems that support aquaculture, whether directly or indirectly. Such representations, exemplified by mathematical models, are designed to help measure, understand, and predict the underlying variables and processes, in order to inform an ecosystem approach to aquaculture." Virtual Technology uses two categories of tools (Ferreira *et al.,* op cit):

- Tools which allow measurements to be made and translate data into information (Information and Communication Technology);
- Modelling tools (the way by which information is used for a given purpose – modelling is used here in a very broad sense) and the link to data collection technology.

This review focuses on the spatial aspects of aquaculture, specifically on the use of one virtual technology tool in each category as it is applied to estimating aquaculture potential, for zoning, for site selection and for carrying capacity. The measurement tool is remote sensing. GIS is the tool that is the spatial platform within which, or coupled to, modelling is carried out. GIS has several relationships to modelling: Embedding GIS into modelling, embedding modelling into GIS, and tight and loose coupling of GIS with modelling (Kapetsky, Aguilar-Manjarrez and Soto, 2010; Figures

7.3a-d). Thus, in this broad sense spatial analysis in aid of aquaculture development and management is modelling. Herein the emphasis is on modelling as it accomplished with the GIS tool with the remote sensing tool as a highly essential but implicit partner.

Perspectives relating to spatial issues in potential, zoning, site selection and carrying capacity and the implementation of the EAA

A recent review analyzed and synthesized information on the status of GIS, remote sensing and mapping applications in aquaculture (Kapetsky, Aguilar-Manjarrez and Soto, 2010). The review was global in expanse. The major findings and conclusions have been summarized by Aguilar-Manjarrez, Kapetsky and Soto (2010). Herein the conclusions have been modified to more closely relate to defining aquaculture potential and implementing zoning, site selection and carrying capacity activities. They also have been categorized in terms of functions and capabilities of spatial analyses, capacities, and advancing implementation.

Functions and capabilities

- An essential element for the implementation of the EAA will be the deployment of spatial planning tools for analysis, decision-making, modelling, and data management.
- The power of spatial analysis is the capability to spatially define ecosystem boundaries where they do not already exist, to enhance existing ecosystem data with data specific to the needs of aquaculture, and then to integrate and analyze the environmental, administrative, social, and economic components of the ecosystem.
- Defining ecosystems spatially is essential to the EAA in order to raise the awareness of aquaculture planners and practitioners to issues that must be taken into account for the further development of aquaculture and for the mitigation of the potential impacts of aquaculture on the environment.
- Spatially comprehensive inventories of aquaculture and its attributes are an essential requirement for implementing the EAA at national and sub-national levels.
- Spatial analytical capabilities can be employed at any scale from global to local
- The most appropriate "scale" for the EAA and for spatial analyses in support of the EAA is defined by the boundaries of the problem expressed in ecosystem, economic, social and administrative terms.
- GIS can support decision-making and modelling within and among all boundaries associated with aquaculture development and management. There are many immediately available decision-making tools that could be used in support of the EAA within GIS and many aquaculture models (e.g. carrying capacity) can be run inside GIS, or be spatially related to aquaculture by GIS.
- Remote sensing already provides historical and real-time information of demonstrated use to aquaculture and the potential for increased use is great. Data and software will become more widely available, user friendly, and accessible to managers rather than just to specialist remote-sensing scientists. Also, archived remote sensing data can be used to analyze change spatially and temporally.

Capacities

- GIS has been implemented in a very broad variety of ecosystems and scales as well as in a wide range of culture systems, but capacities to conduct spatial analyses appear to vary widely among countries.
- Spatial analysis experience in terms of addressing issues in the development of aquaculture and in aquaculture practice and management is good overall. Specific gaps in experience (i.e. know-how) are in economics and socio-economics as well as in multisectoral planning for aquaculture.

- There is a need to identify, qualify and quantify spatial analysis capacities at the country level in order to match training and technical support to the capacity to absorb them.

Advancing implementation

- The success of spatial tools in support of the EAA depends on interest, finances and capacities at international to sub-national levels.
- GIS and spatial analytical techniques should be designed and delivered to match the requirements and capacities of the users.
- The Internet is the most rapid and efficient pipeline for wide ranging technical assistance, for the exchange of data and to communicate in support of the EAA.
- The EAA is holistic and therefore promotion of spatial awareness has to be at the ecosystem level as well as all administrative levels and a broad audience has to be addressed that includes not only aquaculture administrators and the aquaculture industry, but also educators; and high-level decision-makers and NGOs.
- Specific needs include:
  - Increasing GIS-based social and economic analyses in aquaculture.
  - A further exploration and documentation of GIS-based decision support and risk analysis and catalogues of their respective tool boxes.
  - Innovative ways to identify needs and capacities at the national and sub-national levels.
  - Increasing capacities for training in spatial analyses (e.g. via the Internet) in order to reach small, globally dispersed audiences.

Perspectives on the roles of potential, zoning, site selection and carrying capacity in aquaculture development and management

Salient characteristics of aquaculture potential, zoning, siting and carrying capacity, including purpose, scope, scales, data, resolution and results are set out (Table 1) in order to show how these activities relate to one another. Potential, zoning and siting for aquaculture are all development activities that, ideally, follow a temporal and spatial progression beginning with estimating potential and ending with site selection. In terms of spatial scale, potential has the broadest reach, zoning is intermediate and site selection is the narrowest. Carrying capacity has to be considered at all stages and scales of development and management, but is usually most thoroughly analyzed in conjunction with siting. The temporal progression for the former three activities needs to be repeated as culture systems are developed for new species and as culture systems are modified for species already under culture as well as when changing economic situations make locations previously unsuitable newly attractive for investment.

The amount of activity directed towards estimating potential, zoning, siting and determining carrying capacity that has involved the use of spatial tools (GIS, remote sensing and mapping) can be measured in an indicative way by the applications in aquaculture that that are accumulated as publications and characterized as belonging to a set of issues in GISFish[1]. In GISFish, estimates of potential are included in the issues category "Strategic planning for development" and siting and zoning are allocated to the "Suitability of the site and zoning" issue. Thus, insofar as GISFish records are representative of the allocation of spatial analyses to various issues, site selection and zoning were addressed by 29 percent of the 366 applications while strategic planning for development was addressed by 20 percent as of 1 March, 2010 (Kapetsky, Aguilar-Manjarrez and Soto, 2010; Table 6.1). Because publications in GISFish are

[1] GISFish is an FAO-sponsored Web portal. GISFish is a "one stop" site from which to obtain the global experience on Geographic Information Systems (GIS), Remote Sensing and Mapping as applied to Fisheries and Aquaculture. GISFish sets out the issues in Fisheries and Aquaculture, and demonstrates the benefits of using GIS, remote sensing and mapping to resolve them. (www.fao.org/fishery/gisfish/index.jsp)

TABLE 1
Characteristics of estimating potential, zoning, siting and carrying capacity for aquaculture.

Characteristics	Potential	Zoning	Siting	Carrying capacity
Main purpose	Plan strategically for development and eventual management	Regulate development; minimize competing and conflicting uses; maximize complementary uses of land and water	Reduce risk; optimize production	Sustain culture; protect environment/ ecosystem
Spatial scope: Administration	Global to National	Levels 1 and 2 sub-national	Farm or farm clusters	Farm or farm clusters
Spatial scope: Ecosystems	Main environments (freshwater, brackish, marine)	Ecosystem	Portion of ecosystem	Aquaculture ecosystem
EAA Scale	Global	Watershed or waterbody	Farm	Farm to watershed or waterbody
Executing entity	Organizations operating globally; National aquaculture departments	National, state/provincial/ municipal governments with aquaculture responsibilities	Commercial entities	Regulating agencies
Data needs	Basic, relating to technical and economic feasibility, growth and other uses	Basic environmental, social and economic sets	All available	Data to drive models
Resolution	Low	Moderate	High	High
Results obtained	Broad, indicative	Directed, moderately detailed	Specific, fully detailed	Moderately to fully detailed

taken from ASFA and those found in Internet searches, they tend to represent applied research rather than operational applications with the result that the actual number of applications is considerably more than can be accounted for in this way.

Broad-scale estimates of aquaculture potential

A definition of potential is "capable of development into actuality". In this sense the four activities-issues characterized (Table 1) are really one and the same, but compartmentalized in time and space for a better understanding of their respective roles. The purpose of this section is to advocate for taking the broad spatial view and early temporal view, namely estimating potential at national levels. The rationale for estimating potential as a first step towards aquaculture development can be viewed from several perspectives. From a global perspective, the FAO has to allocate scarce resources to identifying and then disseminating "best practices" for development and management of aquaculture, so it is necessary to know with what priority regionally and nationally those resources should be directed. Thus, the results of spatial analyses of potential can be used in the decision-making and allocation process. The same is true at the national and sub-national levels with the aquaculture development and regulatory entities as well as entrepreneurs being the parties requiring estimates of potential in order to plan for development and to attract investment.

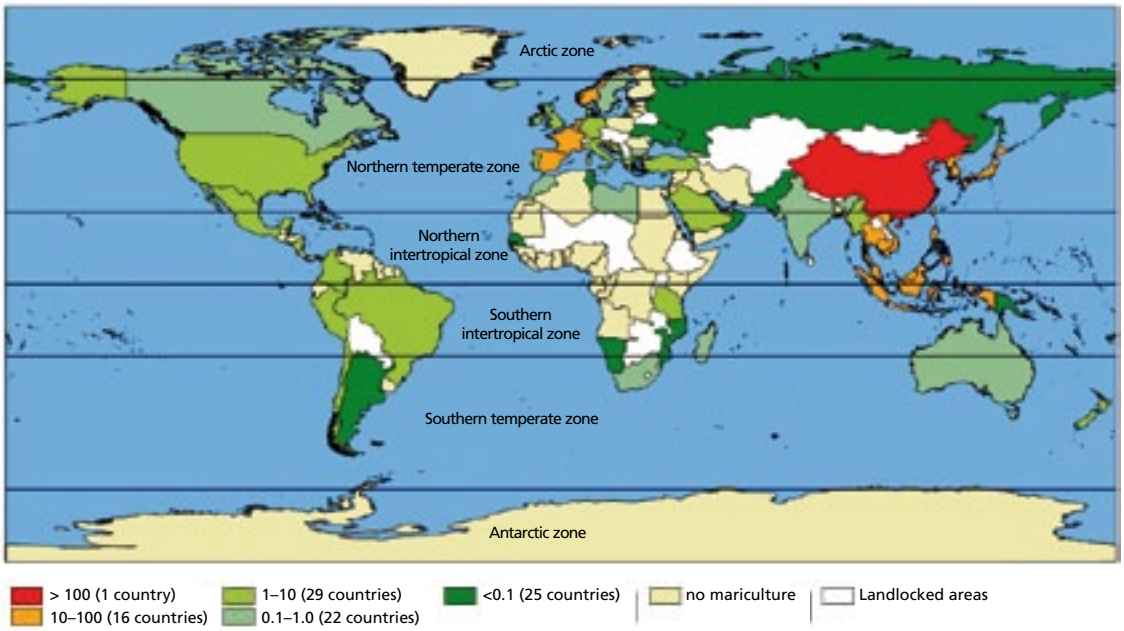
Herein the focus is on broad-scale estimates of potential that have ranged from global to continental and on to sub-continental or regional. It is important to note that global, continental and regional studies of potential are really investigations of potential with the results reported at the national level, but usually with potential spatially identified and quantified in sub-national areas. A fundamental requirement and the main value of such studies is that the results should be comprehensive of all countries in the area of interest and comparable among them. This, in turn, requires a database that is common to the entire area. This requirement is also a constraint because data that are comprehensive and comparable across large spaces are usually of lower resolution than for smaller spaces.

An example of a globally a comprehensive study at the country level that considered the potential effects of climate change on world aquaculture and the issues surrounding

potential climate change impacts (Handisyde *et al*., 2006). GIS was used to develop models to indicate vulnerable areas at the global scale using a broad range of social, economic and climate data. Continental studies of potential for inland fish farming with the innovation that species' growth models were incorporated and population density and travel time were used as surrogates for markets were carried out for Latin America (Kapetsky and Nath, 1997) and for Africa (Aguilar-Manjarrez and Nath, 1998). A regional study for the Caribbean using the same approach was carried out by Kapetsky and Chakallal (1999).

A study on the status and potential of offshore mariculture, a component of the FAO initiative on sustainable offshore mariculture, offers some useful insights on present methods and new ideas for estimating potential that are also relevant for zoning, siting and carrying capacity (Kapetsky and Aguilar-Manjarrez, 2013). Although the study is still not finalized, the study builds on experience already to hand and the basic approach and data sources already have been documented (Kapetsky and Aguilar-Manjarrez, 2007, 2010). The status of mariculture was estimated spatially in terms the intensity of its practice at a national level as mariculture production per kilometre of coastline length thereby providing a contrast with production per country (Figure 1).

FIGURE 1
Intensity of mariculture production (2004–2008) in tonnes per kilometre of coastline and numbers of countries in the range



With regard to estimating potential, spatially defined frameworks are necessary for a common understanding of where and at what pace mariculture can develop. Frameworks can be rigid or flexible. Several rigid, single criterion frameworks –Exclusive Economic Zones, maritime claims and Off-of-the Coast and Offshore as defined by depth ranges – were considered, but found to not satisfy needs for estimating offshore mariculture potential. Rather, a pragmatic set of spatial frameworks, one for each species-culture system combination, that are flexible, integrate a variety of criteria fundamental to development, and that are based on the limits of current mariculture practice, was developed. The criteria included technical, economic, growth environment and other use considerations. In each framework there are three main considerations for estimating

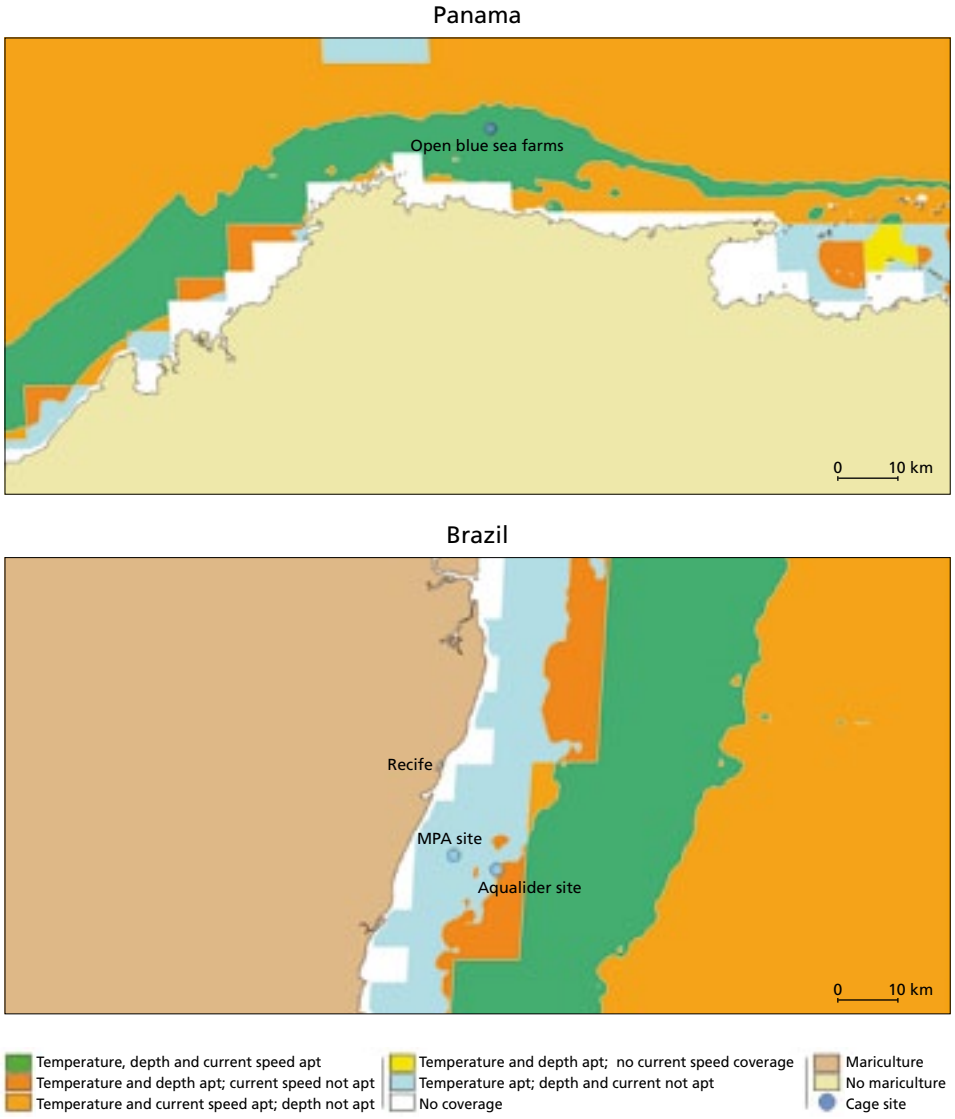
mariculture potential regardless of the size of the area under consideration or the location. They are (1) environments in which it is technically and economically feasible to place culture installations, (2) environments that promote favourable growth and high survival rates of cultured organisms and (3) locations which minimize competing and conflicting uses while taking advantage of possible complementary uses of adjacent space. The first consideration for mariculture development –technical and economic feasibility– was spatially integrated by identifying the coincidence of depths apt for submerged cages and longlines (25–100 m) along with current speeds apt for the former (10–100 cm/s) that are within a cost-effective limit of 25 nm (46.3 km) of a port, the later based on an economic study by Jin (2008). The cost-effective limit emphasizes the operational dependence of offshore culture installations on proximity to essential onshore facilities, goods and services as well as the travel time-distance to maintain economic viability of the operation. The second consideration for mariculture development –environments for favourable growth– was addressed by adopting temperature ranges based on mariculture practice for three species –cobia (*Rachycentron canadum*), 22 to 32 °C, Atlantic salmon (*Salmo salar*), 1.5 to 16 °C and blue mussel (*Mytilus edulis*), 2.5 to 19 °C, and for the latter, a filter feeder, chlorophyll-a >0.5 mg/m^3 was also used to define growth potential. These species are broadly indicative of mariculture potential in that together they span tropical to temperate climate zones, represent fed and extractive aquaculture. Further, they have well established culture systems and world markets. For the latter two potential was also estimated in integrated multiple trophic aquaculture (IMTA). In addition to mariculture, there is a host of potential competing and conflicting uses for the water surface, water column, bottom and sub-bottom even in offshore waters. The objective for mariculture development is to avoid or minimize these uses while taking advantage of uses that would be complementary. Marine Protected Areas (MPAs) were used to illustrate the effect on mariculture potential of possible competing and conflicting uses while taking advantage of possible complementary uses. Results were summarized by numbers of nations and aggregate surface areas meeting the criteria; however, the actual estimates were generated for each Exclusive Economic Zone of each sovereign maritime nation. Status and potential were also tabulated according to ranks of climate zones, and by first ranked maritime nations in each climate zone.

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

(i) **National-level potential and production comparison**: Offshore mariculture potential in square kilometres compared with the mariculture production of nations already practising mariculture of the species-culture system combination at the national level. The rationale for a positive result from this comparison is simply that, where mariculture already exists in a country there is an advantage to its further development.

(ii) **National to local level offshore mariculture potential compared with inshore mariculture locations:** These were comparisons on maps at the national level to the local level of areas found to have offshore potential compared with either the actual locations of inshore mariculture installations of the species or with inshore farming areas in which mariculture of the species was being practised. The rationale is the same as for (i) but with all of the advantages of inshore practice being proximate to offshore areas with potential for development.

FIGURE 4.2 a and b
Areas with temperature apt for cobia mariculture (22–32 °C) and depths (25–100m) and current speeds (10–100 cm/s) apt for submerged cages



(iii) **Offshore mariculture potential compared with actual offshore mariculture locations:** These were comparisons on maps of areas with offshore mariculture potential with the actual locations of offshore installations. These comparisons are the actual verification of the results (Figures 2a and b).

For these comparisons, emphasis was placed on meeting temperature thresholds for all three species, as well as the chlorophyll-a threshold for the blue mussel, as these are the environmental variables used to assess grow-out performance. However, depth and current speed criteria were also taken into account and reported. It was concluded that these comparisons, despite being hampered in some instances by a lack of spatial data coverage in inshore areas, or of no current speed coverage, lend substantial credibility to the conclusion that, by the criteria of this study, there is much unrealized offshore potential for the three species and IMTA offshore of farming areas in nations where the culture of these species is already established.

As a first step towards a new approach to estimating mariculture potential that eventually could become an all-encompassing grid-cell based model, GIS analyses, remote sensing data, and a dynamic Atlantic salmon individual growth model developed

by Stigebrandt (1999) were integrated. The model was used to predict the number of days required to reach a harvestable size of approximately 4.5 kg, a weight used by Jin (2008) in his bio-economic model of offshore farming of Atlantic salmon. The model was run at the locations of a small number of Atlantic salmon farms in Ireland, the Kingdom of Norway, the Republic of Chile and Canada. At first glance, the results are striking. They show an approximate five-month difference in the time required to reach a harvestable size between the Republic of Chile and the Kingdom of Norway. That would translate into a sizeable difference in the number of crops per year and in potential gross sales based on the (apparent) same capital investment in culture facilities between these locations. The Atlantic salmon was selected as a trial species because its pre-eminence in mariculture ensures that data exist to support model building. However, the goal is to move this model to already commercially cultured species, such as the cobia and shellfish that have potential in developing countries.

Features of this study with broad implications for future national level estimates of potential and for more detailed zoning and site selection are the following:

- Spatial frameworks that are easily adaptable to changing situations, that integrate a variety of criteria fundamental to development, and that are based on the limits of current mariculture practice and whose results are verifiable can be used to estimate potential for individual or multiple species-culture system combinations
- This study, based on a few representative species and culture systems along with fundamental technical and economic criteria, shows that spatial analyses can be used to realize a quantitative view of offshore mariculture potential that is comparable with actual inshore mariculture. Viewed from the country level, this approach is a first step towards aquaculture zoning at the national level.
- All but one of the spatial datasets were freely downloadable. This is an important consideration from a developing country viewpoint in terms of availability and cost of the data.
- As a risk aversion approach, locations deemed to have potential were required not only to be within temperature and chlorophyll thresholds, but also the confidence limits on the values had to be within the ranges at the 95 percent level.
- There are additional layers that would improve the characterization of potential at national levels not only for marine aquaculture, but also for inland aquaculture, and that are freely available. These include ecosystems that are already spatially defined and sources for both general and specialized data that have been described by Kapetsky, Aguilar-Manjarrez and Soto (2010; Chapters 3 and 4, respectively).
- Data wholly or partly from satellite remote sensing were indispensable to the analyses. The build-up of long time series of data and advances in sensors and data processing mean that time series "climatology" data are now readily available at increasingly higher resolutions. This will mean that investigations of aquaculture potential, zoning and siting at national to local levels will become more timely and less costly because field verifications will become more spatially focused.
- The approach used to estimate potential for the Atlantic salmon based on modelling the time needed to reach a harvestable size has important implications for future estimates of potential, zoning and siting:
  - Although broad estimates of potential can be based on measures of surface areas that are suitable for development, there is a need to provide measures of potential that are of more immediate use to investors and that are more easily interpretable by aquaculture planners and practitioners. The solution is to integrate or incorporate the models of culture practice and culture economics with spatial models.
  - Another need is to better localize the estimates of potential. The framework approach uses thresholds in rather wide ranges to satisfy criteria and the result is correspondingly large areas in which the actual conditions can vary widely.

Such variation in location can have important operational and economic implications. With the grid-based approach used for modelling relatively small areas, nominally 5 km^2, cells can be queried for temperature and such queries can be extended to the other critera (e.g. bathymetry, current speed).

Siting aquaculture and zoning

Aquaculture siting criteria known to be important for a species, culture system or combination of the two are well known since the 1980's For example, a consultation/ seminar was devoted to entirely to coastal pond engineering for aquaculture with 20 background papers (SCS, 1982) many of which dealt directly with siting criteria (Hechanova, 1982; Adisukresno, 1982); or with factors important for siting such as seasonal and long term variations in factors important for siting (Kapetsky, 1982a) or with environmental impacts (Kapetsky, 1982b). Site selection criteria for aquaculture development continue to be set out as required for new species, new culture systems, or for new environments along with the limitations placed on them by other uses of land and water such as offshore marine space. As an example of site selection for a new environment, offshore criteria have been described by Benetti (2010), and the IUCN (2009) has devoted 300 page guidebook to site selection and management aimed at Mediterranean aquaculture. This guidebook includes a chapter on the fundamentals of GIS and its applications to site selection and site management. Apart from the technical description of analytical capabilities, is a reminder that GIS should also be used in a participatory way in order to foster discussion among stakeholders and to identify the issues.

Siting and zoning of aquaculture are tasks within a spatial and temporal continuum of aquaculture development and management (Table 1) and the general approach will be similar to that already set out above for estimating potential except that many more criteria will be involved and the task will be much more localized spatially. Regarding criteria, the fundamental task is to bring the list of criteria into a spatial domain where their individual and collective consequences can be objectively evaluated.

The earliest use of GIS and remote sensing for aquaculture siting is credited to Mooneyhan (1985) who developed a siting simulation as a training exercise. A review of GIS and remote sensing applications in aquaculture with a section on those pertaining specifically to siting was made by Kapetsky (2004). Suitability of the site and zoning have been one of the most active issues in aquaculture addressed by GIS as measured by GISFish records, accounting to 25 percent of 157 applications in an evaluation that covered the period 1985 – 2002 (Kapetsky and Aguilar-Manjarrez, 2004), and most recently, 29 percent of 366 applications up to March, 2010 (Kapetsky, Aguilar-Manjarrez and Soto, 2010). In a review of GIS, remote sensing and mapping in marine aquaculture there were seven applications among a total of 15 that focused on suitability of the site and zoning for marine fish in cages; however, among 23 applications on marine shellfish only two dealt with suitability of the site and zoning (Kapetsky and Aguilar-Manjarrez; 2007; Tables 3.4 and3.5). More recently, case studies exemplifying GIS, remote sensing and mapping applications as applied to EAA principles have been characterized among which three pertained to the suitability of the site (Kapetsky, Aguilar-Manjarrez and Soto, 2010; Table 8.1). Two applications on siting have been featured as case studies in GISFish. Case studies are particularly valuable because, unlike most journal articles and technical reports, the kinds of expertize employed, the duration of the study and relevance of GIS or other spatial tool are set out along with the issues addressed, methods and results.

The share of activities devoted to the suitability of the site and zoning indicate that there is considerable experience in employing spatial analyses to resolve siting and zoning issues. However, an important consideration for aquaculture development is where that experience lies. In this regard, up to December, 2009, 298 applications in GISFish, including all issues, could be associated with only 50 countries as against

163 countries with aquaculture production at that time. Visits to GISFish provided a slightly more encouraging, but not directly comparable picture with a monthly average of visits from 66 countries each month (Kapetsky, Aguilar-Manjarrez and Soto, 2010; Chapter 9). Thus, the dissemination of the siting and zoning experience is an issue to be resolved and a present apparent bottleneck.

Studies dealing with zoning are less common than for site selection. Among recent applications of GIS and remote sensing-based applications, those dealing with sustainable zoning of aquaculture management areas for mussel farming in the Bay of Plenty, New Zealand stand out as providing a coordinated holistic approach (Longdill *et al*., 2007; Longdill, Healy and Black, 2008).

Carrying capacity

Carrying capacity is the most flexible activity temporally in that it could be applied at any time along the continuum from potential to zoning and on to site selection (Table 1), and like the others, it will be reapplied in the same locations in response to changing situations. In fact, carrying capacity can be usefully viewed in a temporal sequence as portrayed in a review of carrying capacity for bivalve culture in which carrying capacity has been separated into four functional categories by McKindsey *et al.* (2006) based on an earlier classification by Inglis, Hayden and Ross (2000): i) physical carrying capacity — the total area of marine farms that can be accommodated in the available physical space ii) production carrying capacity — the stocking density of bivalves at which harvests are maximized, iii) ecological carrying capacity — the stocking or farm density which causes unacceptable ecological impacts, iv) social carrying capacity — the level of farm development that causes unacceptable social impacts. Regarding physical carrying capacity McKindsey *et al.* (op cit.) state that the concept describes the area which is geographically available and physically adequate for a certain type of aquaculture. That corresponds closely to estimates of potential as described herein. McKindsey *et al.* (op cit.) recommend GIS for the analyses of physical carrying capacity. In their view production carrying capacity could be determined by combining interactive input for data such as the species to be farmed with stored data from the GIS or other database. They note, too, that the calculation of ecological carrying capacity relies heavily on models, and the data for these models can be extracted from a GIS and fed into a series of model calculations. In relation to social carrying capacity they emphasize that social aspects are qualitatively different from the other categories of carrying capacity and thus require their own treatment. One of the problems they note is less geographical definition for the people and institutions that would be involved with it, but miss the potential for GIS to be assistance in defining the limits of social carrying capacity in space and the connections among the components. They rightly note that another problem of incorporating social capacity into a comprehensive carrying capacity evaluation system is that the criteria are not clearly defined. Again, they overlook the opportunity afforded by GIS and spatial analysis to contribute to better definition of criteria by providing a framework that locates each aquaculture component spatially along with its attributes and functional relationships with the other components. This would amount to one part of an aquaculture management information system. A similar information system is approved for implementation on a pilot scale in two provinces in the Kingdom of Thailand as an FAO Technical Cooperation Programme project. This project involves establishment of a system and mechanisms for channelling management information and decision-making needs from stakeholders to the responsible Department of Fisheries divisions and research centres and to expedite solutions back to stakeholders within an Aquaculture Information Management System as the backbone and basic geo-framework and attributes.

Finally, expert systems are suggested by McKindsey *et al.* (op cit.) to deal with the complexity and many kinds of expertize needed to implement carrying capacity. Within that idea, "fuzzy" expert systems are advocated to deal with inadequate amounts of data and uncertainties about boundaries. Fuzzy analytical techniques are available in GIS as parts of decision support systems (e.g. Manifold™ by CDA International Ltd and Idrisi by Clark University) but they require expert knowledge in order to take informed decisions about uncertainties.

Looking more broadly, carrying capacity is not set apart as an individual issue in GISFish, however, tapping into GISFish information by querying abstracts among aquaculture publications shows that there were 18 applications in which "carrying capacity" was included in an abstract up to November, 2010. Carrying capacity was broadly associated among issues. Six applications related to the environmental impacts of aquaculture issue, five were associated with suitability of the site and zoning, three with strategic planning for development, two with the inventory and monitoring of aquaculture and one each with anticipating the consequences of aquaculture and planning for aquaculture among other uses of land and water. Thus, carrying capacity spans a broad spectrum of spatial issues in aquaculture.

Definitions and tools for measuring carrying capacity are presented in the context of the Guide for the Sustainable Development of Mediterranean Aquaculture (IUCN, 2009) already mentioned in the context of site selection above. Brief descriptions of 16 carrying capacity models are set out in the guide's Table P1, pp. 210. Of interest herein are the spatial scales at which the models operate. Five operate at waterbody scale, three at cage scale, two operate at both waterbody and regional scale and one at cage and waterbody scale. There were no models operating solely at regional scale. The remaining are individual-based models, or dimensional models whose scale is set by the application.

Attention is called to applications that include carrying capacity as one of their functions, or that have that activity as an objective, and also in so far as they incorporate multiple models, multiple species, broad scales and the possibility that they could be adapted to contribute to broad scale applications such as the global study of mariculture potential described above, or when applied at the national level as a part of a broad process of estimating aquaculture potential. Several such applications, (Filgueira and Grant, 2009 on blue mussel ecosystem level carrying capacity; Dallaghan, 2009 on waterbody to farm level shellfish models for decision support to industry; Ferreira, Hawkins and Bricker (2007) and Silva (2009) on using the FARM siting and decision model in data-poor situations) have already been recognized as important examples of virtual technology and have been set out as case studies by Ferreira *et al.* (2012). Other applications that have been recognized as innovative with respect to spatial analyses within the framework of the EAA have been selected as case studies by Kapetsky, Aguilar-Manjarrez and Soto (2010; Chapter 8) among which carrying capacity, site selection and zoning of aquaculture parks were untaken for farm clusters by Palerud *et al.* (2008) Legović *et al.* (2008) and White (2009). A decision support tool was developed by Hunter, Telfer and Ross (2007) and Hunter (2009) based on sub-models for cage site suitability, particulate waste dispersal, biodiversity sensitivity and visual landscape capacity in an archipelago. A four-country project to locate high potential aquaculture areas based in part on analysis of farmer's perceptions of the technology and the likelihood that they would adopt it was reported by Kam *et al.* (2008).

Two other case studies are described here in somewhat more detail to give the scope and flavor of applied research that is on the way to becoming the widespread practical applications of the near future. With these criteria in mind, one of the most innovative and widely operational applications is AkaVis (Ervik *et al.*, 2008, Ervik *et al.*, forthcoming); described by Ferreira *et al.* (2012). It is an "all-in-one" Web-based interactive decision support system including site selection, carrying capacity and management monitoring modules. The interactive capability allows the users to immediately see the consequences of their choices. AkaVis combines a broad scale

approach by covering the Kingdom of Norway's coastal aquaculture and multiple species by including the main fish and shellfish under culture. Moreover, it is holistic in EAA social terms by being designed for transparency, public participation and outside scrutiny. From a technical viewpoint, it is model driven on grids. The system integrates: (i) data regarding environmental parameters (ii) expertize (e.g. growth models, rules for weighting parameters and boundary values); (iii) legislation, regulations and directives (e.g. distance to other aquaculture sites); (iv) calculations, visualizations and interactivity with the user; and (v) basic and thematic maps.

Another innovative application is SPEAR – Sustainable Options for People, Catchment and Aquatic Resources (Ferreira *et al*., 2008; described as a case study for spatial decision support by Kapetsky, Aguilar-Manjarrez, and Soto, 2010 and as a virtual tool by Ferreira *et al*., 2012). The spatial perspective is coastal zone management in the People's Republic of China in two pilot study areas where aquaculture is an important economic activity. The aim was to provide guidance to aquaculture administrators on sustainable carrying capacity that could be made more specific at operational levels. Spatially, SPEAR operated not only in the aquatic realm, but also included the surrounding catchments. Noteworthy features are the use of multiple models at different scales including an economic model, multiple species and a temporal scale of three years for simulation of consequences of management options. GIS was used throughout the project by providing the geographic component for key variables, in modelling by providing input values, a platform for communication between different models, in verification and for visualization and for spatial analyses of model results.

Summary and conclusions

The task assigned for this review, to cover key drivers and issues surrounding carrying capacity and site selection, with emphasis on global versus local modelling and with regard to the Ecosystems Approach to Aquaculture (EAA), has been expanded to include estimating potential and zoning as additional activities and issues. This is because most aquaculture development and management issues, including potential, zoning, siting and carrying capacity, are largely driven by spatial considerations. Thus, one of the key frictions on aquaculture development is in locating the appropriate space for development. For this reason this review focuses on the spatial aspects of aquaculture.

Computerized spatial analyses have been used to address the "What, where, and how much?" of production activities since the early 1980's, but the EAA provides an additional impetus to use spatial analyses to expand to analyses of "For whom and with what social, environmental and economic consequences?" as obligatory additional questions. The underlying objective is to highlight ways through which leveraging the deployment of spatial analyses could contribute more fully to aquaculture development by becoming more widespread and more effective. This objective should have two components, the first of which is an overview of the state of purely technical aspects of estimating potential, carrying capacity, site selection and associated activities. The second component is equally important. It is the effective and timely dissemination of the packaged know-how of these techniques to the aquaculture development and management community. This component requires priority attention, but other than calling attention to it as an important issue and bottleneck, its implementation is beyond the scope of this review.

Perspectives on spatial issues in potential, zoning, site selection and carrying capacity with regard to the implementation of the EAA

These conclusions were originally generated with the entire spectrum of spatial issues in aquaculture in mind; however, they pertain equally well to the more focused issues relating to potential, zoning, site selection and carrying capacity. From the perspective of functions and capabilities to deal with the general issues and those specific to

this review, the power of spatial analysis is the ability to spatially define ecosystem boundaries where they do not already exist, to enhance existing ecosystem data with data specific to the needs of aquaculture, and then to integrate and analyze the environmental, administrative, social, and economic components of the ecosystem. The fact that spatial analytical capabilities can be employed at any scale from global to local means that the appropriate "scale" for spatial analyses in support of potential, zoning, siting and carrying capacity is defined by the boundaries of the problem expressed in ecosystem, economic, social and administrative terms.

From the perspective of spatial analytical capacities, technical capabilities to support aquaculture in general are good overall, but there are gaps in experience in economics and socio-economics as well as in multisectoral planning for aquaculture that relate directly to EAA needs that are for spatial definition of economic and social components of ecosystems. Competence in these areas can be improved. However, more challenging are indications that available know-how for spatial analyses is not reaching countries and situations where it could be put to good use. This leads to the question on how spatial analyses in support of aquaculture can be advanced. One avenue for advancement is through promotion. Promotion of spatial awareness of aquaculture has to include all levels and boundaries of governance. Furthermore, a broad audience has to be informed that includes not only aquaculture administrators and the aquaculture industry, but also educators, high-level decision-makers and NGOs and other stakeholders.

The Internet is the most rapid and efficient pipeline for wide ranging technical assistance, for the exchange of data and to communicate in support of the sustainable development of aquaculture within the EAA. Innovative ways to identify needs and capacities top absorb technical assistance at the national and sub-national levels are urgently needed.

Perspectives on the roles of potential, zoning, site selection and carrying capacity in aquaculture development and management

Potential, zoning and siting for aquaculture are all development activities that, ideally, follow a temporal and spatial progression beginning with estimating potential and ending with site selection. In the spatial scale, potential has the broadest reach, zoning is intermediate and site selection is the narrowest. The temporal progression of these activities needs to be repeated as culture systems are developed and changing economic situations make locations previously unsuitable newly attractive for investment. Carrying capacity has to be considered at all stages of development and management.

Broad-scale estimates of aquaculture potential

Estimating potential at national levels is advocated as a first step towards aquaculture development in countries where aquaculture is little developed or not yet practiced and as a useful additional step towards effectively planning for development and to attract investment in countries where aquaculture is developing rapidly.

The use of spatial frameworks to estimate aquaculture potential for all maritime nations has been summarized. The frameworks used for the analyses are easily adaptable to changing situations, integrate a variety of criteria fundamental to development, and are based on the limits of current mariculture practice. The results are verifiable and can be used to estimate potential for individual or multiple species-culture system combinations.

The long-term trend for increasing facility to carry out spatial analyses, and increased quality, higher resolution and free availability of data continues. This will mean that investigations of aquaculture potential, zoning and siting at national to local levels will become more timely and less costly because verifications will become more spatially focused and less time will have to be spent in the field to carry them out.

There is a need estimate aquaculture potential in terms that are of more immediate use to aquaculture planners and practitioners and that are more easily interpretable by investors. Suitable surface areas are currently available, but an example has been given of time to reach harvestable size as one of many better indicators. The solution is to integrate or incorporate the models of aquaculture development and management (e.g. carrying capacity) into to broad scale spatial analyses that generate estimates that are localized.

Siting aquaculture and zoning

Suitability of the site and zoning have been the most active issues in aquaculture addressed by GIS indicating that there is a considerable build-up of experience in employing spatial analyses to resolve siting and zoning issues; however, dissemination of the experience among countries is an apparent problem. Zoning and siting are tasks within a spatial and temporal continuum occurring after potential has been established. Siting criteria known to be important for a species, culture system or combination of the two are well known. The fundamental spatial analytical task, in line with the EAA is to integrate the many criteria for siting and zoning into a spatial domain where their individual and collective consequences can be objectively evaluated in environmental, economic and social terms.

Carrying capacity

Carrying capacity, considering the continuum of activities from estimating potential to zoning and on to site selection, is the most flexible activity temporally in that it could be applied at any time in the course of development and management. Like the other activities, carrying capacity is iterative and will need to be periodically reassessed in response to changing environmental, economic, and social situations. Estimates of carrying capacity should be integrated with investigations of potential. There are many opportunities to employ spatial analyses to resolve technical issues in carrying capacity, but the capabilities of GIS to better define the limits in space of social carrying capacity, to contribute to identifying social carrying capacity criteria and to deal with data limitations for decision-making through fuzzy analysis have been overlooked.

Main conclusions and recommendations

There is a clear trend for "all-in-one" applications that include multiple objects (species at different trophic levels and varied culture systems), incorporate multiple functions basic to aquaculture development and management (site selection, carrying capacity, monitoring for management including legal aspects), that take into account ecosystem level spatial boundaries, involve active participation or scrutiny by the public and that produce outputs that are highly relevant to managers, commercial entities and to aquaculture practitioners. Spatial analyses have a fundamental support role in these applications. These developments, briefly reviewed in the section on carrying capacity, underline the fact that individual issues such as site selection have a very a narrow scope in present day and future aquaculture and that the capability exists to address many complex problems through imaginative integration of the many models that are available.

There is a need to extend the temporal scale of the "all-in-one" applications so that they can be implemented early on in aquaculture development planning in a precautionary way rather than later on in a reactive way. There is a need, too, to broaden the spatial scope of such applications so that they can be implemented at national levels even with the disadvantage of less certainty in the results that will be compensated for by savings gained by more focused, less time consuming and less expensive field verifications. The main bottlenecks to implementing broad scale spatial analyses that include "all-in-one" aquaculture development and management applications are partly data of appropriate resolution but more restrictively, lack of the variety of data needed as input to the models.

All in all, technical capabilities to deal comprehensively with aquaculture issues in space and time are rapidly improving. This contrasts with the apparent problem of disseminating the techniques and building the capacities to utilize them.

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Some basic hydrodynamic concepts to be considered for coastal aquaculture

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Abstract

Some basic hydrodynamic concepts that may influence coastal aquaculture activities are presented. Moreover, a pair of simple criteria for deciding whether it makes a difference to locate a cage or cluster on one side of a basin or the other is presented. These criteria are based on the non-dimensional Ekman and Kelvin numbers. Finally, a simple criterion based on tidal excursion at an aquaculture site is proposed for optimal cage or cluster separation. This criterion allows determination of "ellipses of influence" for a given cluster or cage, which indicates the potential area in the body of water that may be influenced by suspended and dissolved materials associated with aquaculture activities.

Introduction

The concepts described herein may apply to mariculture and to aquaculture activities in brackish waters, i.e. coastal aquaculture. According to FAO (2007), coastal aquaculture accounts for 50 percent of the worldwide production of fish, crustacean and molluscs in terms of the fishery value. As far as quantity is concerned, coastal aquaculture (brackish water culture and mariculture) accounts for 43 percent of the world's production. Clearly, coastal aquaculture in the world provides a sizable source of food and economic prosperity. A basic question that arises is: how sustainable is coastal aquaculture? This is an easy question with a very difficult answer. An attempt to begin an answer is presented here. In particular, a simple criterion based on tidal excursion at an aquaculture site is proposed for optimal cage or cluster separation.

Many coastal aquaculture farms are located in estuaries, where the interaction between riverine and oceanic waters determines the capacity of the estuary to flush. This capacity to flush a semi-enclosed coastal body of water is what motivates the need to understand its circulation features. Aquaculture activities in a well-flushed system will certainly have a lesser impact on the environment, and in turn the environment will have lesser effects on the organisms being cultured, than aquaculture activities in a poorly flushed system. Well-flushed basins should make aquaculture more sustainable, or have a larger carrying capacity (ability of a system to sustain the activity), than poorly flushed basins. In the latter, water and sediment

quality deterioration from aquaculture-related activities would limit the productive period of the basin and drastically limit its carrying capacity. Even within a given basin, flushing will be more efficient at some locations than at others because of the way the water circulates. Therefore, in order to make the best decision on the appropriate site for aquaculture activities, and to increase the carrying capacity of a basin, it is imperative to understand the temporal and spatial variability of its circulation and its mass field (temperature, salinity and density).

This presentation seeks to synthesize the most salient aspects of temporal and spatial variability of water circulation, with special emphasis on estuaries, in order to help optimize size selection decisions at those environments. Examples of aquaculture activities in estuaries abound all over the world, e.g. Canada, Scotland, the Kingdom of Norway, the Republic of Chile, the Socialist Republic of Viet Nam, People's Republic of China, Central America. The concepts presented here apply, in one way or another, to all or most estuarine systems. This paper presents a section on circulation in estuaries, followed by a section that links the circulation to flushing times and carrying capacity. A section that describes a potential tool for determining carrying capacity, to be implemented in 3 phases, follows the presentation. The paper closes by proposing a criterion for siting contiguous aquaculture clusters, before presenting a brief paragraph with summary and recommendations.

Circulation in estuaries

Circulation in estuaries, and in any basin, determines its capacity to flush or self-clean. In this section the basic structure of estuarine circulation is presented. A discussion on how tides, earth's rotation, bathymetry, winds and water balance affect the basic circulation structure is also presented.

Basic Circulation Structure

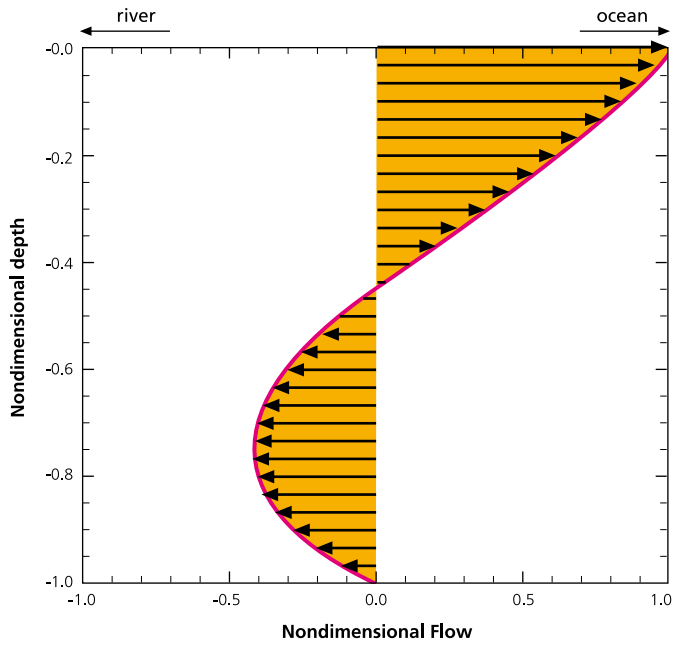
An estuary is characterized by the mixture of salty oceanic water and fresh water, from rivers or glaciers, in a semi-enclosed basin. This definition, however, does not apply to estuaries in arid regions where the physical process controlling the long-term circulation, namely water density gradients, is essentially the same as that in temperate and high latitude estuaries. That is why it is not crucial to get distracted by definitions of estuaries. Instead, it is practical to follow the arguments of US Supreme Court Justice Potter Stewart, who in 1964 said that pornography is hard to define but that you know it when you see it. The same can be said about estuaries, it is hard to provide an all-inclusive definition but they are identifiable upon sight. Fjords are also estuaries, found in high latitudes where they were carved by glaciers, and represent basins with typical intense aquaculture activities. Rias, found in tectonic areas in the Iberian Peninsula, are estuaries with intense aquaculture activities, too.

The interaction between riverine and oceanic waters causes a long-term circulation that appears from averaging the water motion over one or several tidal cycles. Riverine waters are less dense because they have less salt relative to ocean waters and will move along the surface of the estuary toward the ocean. Heavy ocean waters will exhibit a net landward motion along the bottom layers of the estuary (Figure 1). This two-layered, vertically sheared or vertically varying, circulation is typically known as *gravitational circulation* or *density-driven circulation*. It has traditionally been called *estuarine circulation*, but the name is not necessarily accurate because the circulation in estuaries, the true estuarine circulation, is driven by additional processes; not only by density gradients. For a thorough review on these definitions, see e.g. Valle-Levinson (2010). Independently of how it is called, this net circulation, caused by freshwater forcing, is modified by tidal forcing to establish the ability of the estuary to flush and its carrying capacity.

Tidal variability

The net circulation in estuaries or density-driven circulation, as mentioned above, consists of net surface outflow and net bottom inflow resulting after averaging out the tidal influence. However, the tide itself may modulate the strength of the density-driven circulation by causing more vigorous mixing during spring tides (tides with largest range in the month – highest tides and lowest tides) than during neap tides (tides with the smallest range). Enhanced vertical mixing between relatively fresher and saltier waters during spring tides will dampen the density-driven circulation in an estuary and its ability to flush. In neap tides, the density-driven circulation is expected to be more robust than during spring tides because of reduced mixing.

FIGURE 1
Gravitational circulation showing net surface outflow and net bottom inflow



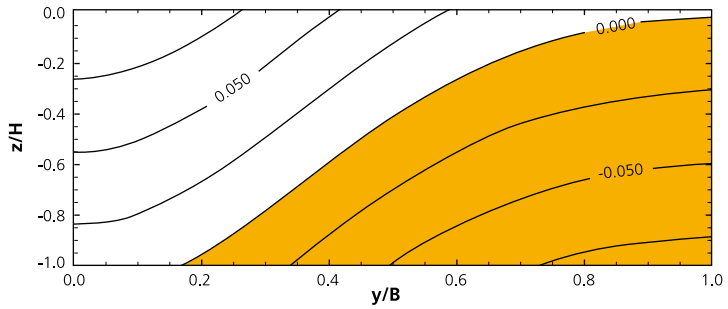
Tides not only modify the mass field in an estuary by modulating vertical mixing, they also produce a net or average circulation. This tidally driven net circulation is produced by the distortion of tidal waves as they enter and propagate into an estuary. The net circulation produced by tides in semi-enclosed basins can counteract the effects of the density-driven circulation. In its simplest form, the net circulation caused by tides consists of surface inflow and bottom outflow. In most cases, this circulation is rather weak, compared to the gravitational circulation. But in some cases, where the tidal range is greater than one tenth of the estuary's depth or where the tide is distorted by reflection on the basin's walls, tidal net flows need to be taken into account. In the case when flow produced by tidal distortions is important, it may dominate the long term circulation and flushing of the estuary, i.e. ultimately will dictate its carrying capacity.

Influence of earth's rotation

In addition to being modified by tides, the gravitational circulation in estuaries can be influenced by earth's rotation through the Coriolis effect or Coriolis accelerations. In essence, Coriolis accelerations deflect flows to the right in the northern hemisphere and to the left in the southern hemisphere. This effect is only appreciable to an observer on a reference frame that is fixed in space, a non-inertial reference frame. When modified by earth's rotation, the gravitational circulation in northern hemisphere estuaries will therefore tend to exhibit stronger outflows on the left side of the estuary (looking landward) than on the right. Similarly, inflows will be stronger on the right side of the estuary than on the left. The gravitational circulation thus will exhibit a lateral structure and a vertical structure (Figure 2). The consequence of earth's rotation effects is that one side of an estuary will flush buoyant fluids and particles more efficiently than the other. This segregation of flushing efficiency should be considered for selecting the site of aquaculture facilities.

As can be seen, it is essential to determine whether an estuary is influenced by Coriolis effects or not. The typical criterion used to determine the importance of earth's

FIGURE 2
Gravitational circulation (in m/s) affected by earth's rotation in a rectangular channel (looking into the channel)



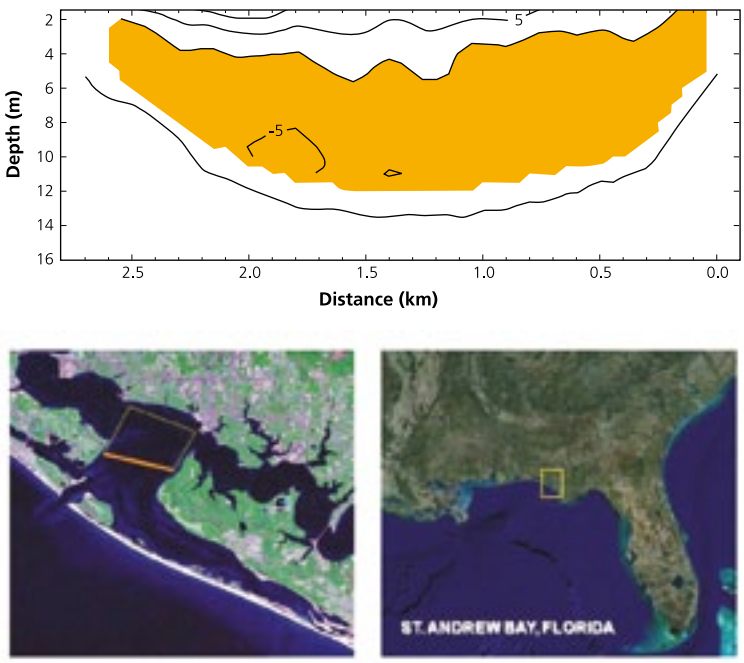
Note: White shaded contours represent seaward along-channel flow.Dark-shaded contours denote flow into the channel (away from the observer)

rotation in a fluid motion requires that the basin is wider than the internal radius of deformation, or internal Rossby Radius, R_i:

$$R_i = \frac{\sqrt{g\frac{\Delta\rho}{\rho_0}H_1}}{f}$$

where $\Delta\rho$ is the density contrast between outflowing and inflowing waters in the basin, g is the acceleration due to gravity, ρ_0 is a reference water density, f is the Coriolis parameter (O 10^{-4} s^{-1}) and H_1 is the layer of the outflowing (or inflowing) water. Thus, the internal Rossby Radius has units of length. However, not only the width of the basin dictates whether earth's rotation will affect the motion or not. The dynamical depth of the basin may also determine whether Coriolis effects are influential or not. The dynamical depth is characterized by the fraction of the water column H occupied by the depth of frictional influence, sometimes referred to as Ekman layer depth d (e.g. Kasai *et al.*, 2000). Such non-dimensional dynamical depth is analogous to the inverse of the Ekman number, which will be defined in the following paragraph. In basins where H/d >~ 4, a dynamically deep basin like a fjord, Coriolis effects become most evident. But even in narrow basins (narrower than the internal Rossby radius), lateral flows produced by Coriolis accelerations may re-distribute mass and momentum across the basin. Therefore, these accelerations may be quite important in modifying the basin's flushing efficiency.

FIGURE 3
Mean flows in St Andrew Bay estuary, Florida, on the Gulf of Mexico. Upper panel shows contours of mean flow (in centimeters per second) with the same convention as on Figure 2. Lower left panel shows the location of the transect shown in the upper panel



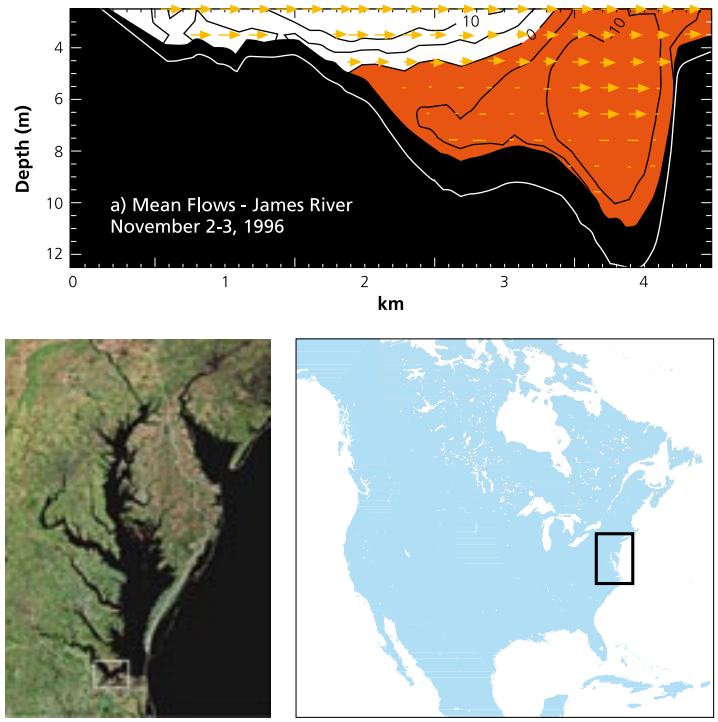
Note: Upper panel shows contours of mean flow (in centimeters per second) with the same convention as on Figure 2. Lower left panel shows the location of the transect shown in the upper panel.

Earth's rotation effects may be further understood in terms of the competition between Coriolis accelerations and frictional influence. This competition between friction and Coriolis accelerations is characterized by the nondimensional Ekman number Ek. When friction is weak, even negligible, Ek is << 1 and the density-driven flow will exclusively

be modified by Coriolis acceleration. An example of this situation may be illustrated with measurements of net exchange flows, averaged after one tidal cycle, in a subtropical estuary of the Gulf of Mexico (Figure 3). The flow structure in St Andrews Bay on the western Florida coast exhibit vertical variability in the exchange flow, with outflow toward the ocean at the surface and inflow underneath. The outflow is strongest on the left hand side of the cross-section, looking landward, because of the earth's rotation effects.

On the other hand, when *Ek* is close to 1, friction overwhelms Coriolis and earth's rotation effects are unimportant. In this situation, the exchange flow associated with gravitational circulation might be more laterally variable than vertically variable. This is illustrated with measurements of net exchange flow in a temperate estuary, tributary to the Chesapeake Bay in the eastern coast of the United States (Figure 4). The cross-section at the James River shows net inflows in the deepest part of the cross-section, extending from the bottom to the surface. Net outflows are found segregated to the shallowest portions of the section, also occupying the entire water column. It is evident from the two examples shown in Figures 3 and 4, that the location of an aquaculture facility near the left of the estuary (looking landward) would cause different environmental impacts at each of the two estuaries. Therefore, it is essential to determine the structure of net exchange flows and its variability through time in order to help select an appropriate site for aquaculture activities.

FIGURE 4
Mean flows for a transect in the James River, Virginia, in the Chesapeake Bay. Arrows represent transverse flows (not discussed)



Influence of Bathymetry

In addition to the competition between earth's rotation and friction, the shape of the bottom, or bathymetry, can play a determinant role in shaping the net exchange flow structure in a basin. Theoretical results of density-driven flows, supported by observations in several estuaries, show that different bathymetric shapes yield vertically or horizontally sheared flows (Figure 5). When a channel has steep bathymetry, as in a triangular or V-shape, the exchange is laterally varying. But as the channel becomes flatter and flatter, as in a U-shape, the exchange becomes vertically varying. These results underscore the statement that the location of aquaculture activities may produce different environmental effects whether they are established on one side of the estuary or the other.

Influence of Wind

Wind forcing may also alter the gravitational circulation in estuaries. When the wind blows in a semi-enclosed basin, it drags the surface waters in approximately the same

FIGURE 5
Gravitational circulation (normalized by maximum inflow) modified by bathymetry. Same contour convention as in Figures 2, 3 and 4

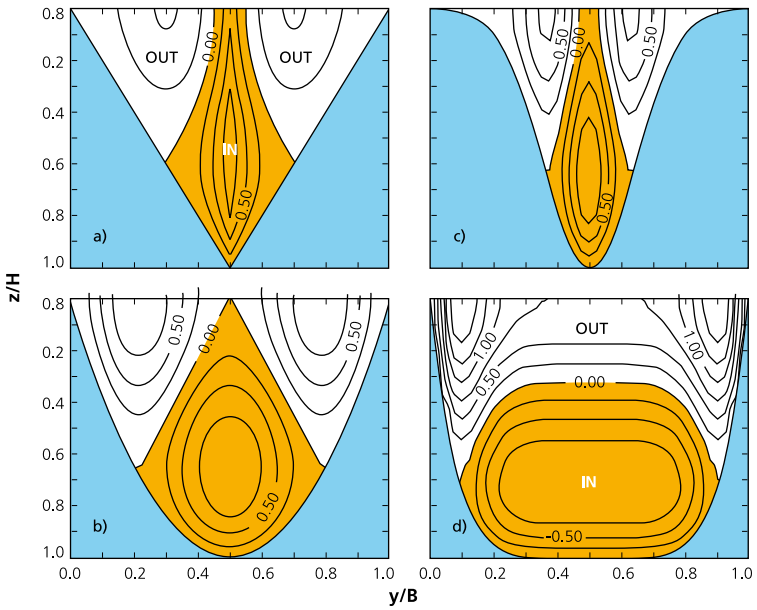
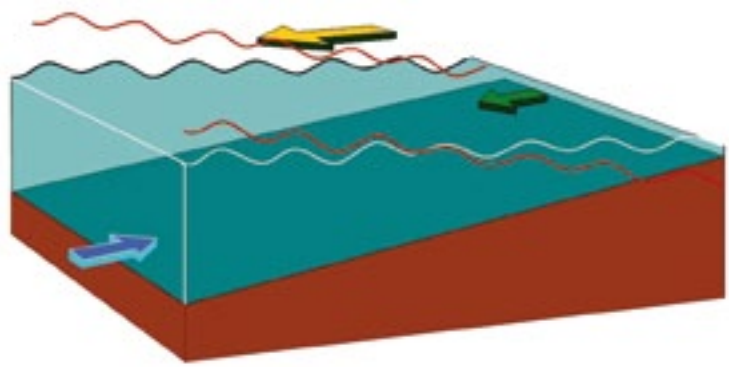


FIGURE 6
Diagram of wind-driven flow in a channel



Note: Yellow arrow represents wind. Green arrow is downwind flow at surface and blue arrow is upwind flow. The water surface is distorted by wind from the white lines to the red lines.

direction in which it blows. This wind-driven transport piles water up in the downwind direction, causing a water level slope inside the basin (Figure 6). In turn, the water level slope drives a near-bottom circulation that moves in the opposite direction to that of the wind blowing at the surface. In essence, the response of a semi-enclosed basin to wind forcing is downwind flow at the surface and upwind flow at depth. Thus, a seaward wind should reinforce the gravitational circulation and a landward wind will oppose it. In any estuary, it should not be uncommon to have seaward or landward winds that reinforce or retard the density-driven flow. It is essential to recognize these interactions in order to understand the flushing efficiency of the basin.

In the same way that bathymetry modifies the density-driven flow, bathymetry can also shape the structure of wind-driven flows. In a similar way (Figure 5) for density-driven flows, a V-shaped bottom configuration produces laterally varying wind-driven exchange flows (Figure 7). Analogously, a U-shaped bathymetry favors the vertically varying exchange pattern. Therefore, depending of the shape of a basin's bathymetry, some portions of the coastline will be more favourable for aquaculture activities in terms of their potential impact on the environment, and ultimately on their own sustainability.

Influence of water balance

In tropical and subtropical latitudes, the influence of riverine waters may be sporadic or completely absent. At those latitudes, the balance between water losses caused by evaporation and water gains from pluvial precipitation can modify the water balance in the estuary and produce reverse circulations. In the case that evaporation exceeds precipitation, the water density inside the basin will become greater than the density of the adjacent ocean. This will favour the development of near-bottom waters flowing toward the ocean and near-surface waters flowing from the ocean

toward the basin. This is called inverse gravitational circulation. Because there is a net water loss from evaporation in the basin, the ability of an inverse estuary to flush will be drastically reduced as compared to a normal estuary. Similarly, there are basins that exhibit inverse circulation conditions part of the year, during a dry season, and typical gravitational circulation during the wet season (Figure 8). Water quality conditions in these systems are clearly worsened during the dry season. Therefore, inverse estuaries or seasonally inverse estuaries are prone to exhibit more serious water quality problems because of their reduced flushing efficiency. These natural variations may have deleterious effects for aquaculture activities and in turn, these activities could be more damaging to these susceptible environments.

FIGURE 7
Wind-driven circulation (in m/s) modified by bathymetry (analytical expression for each bathymetry is shown). Same contour convention as in Figures 2, 3 and 4

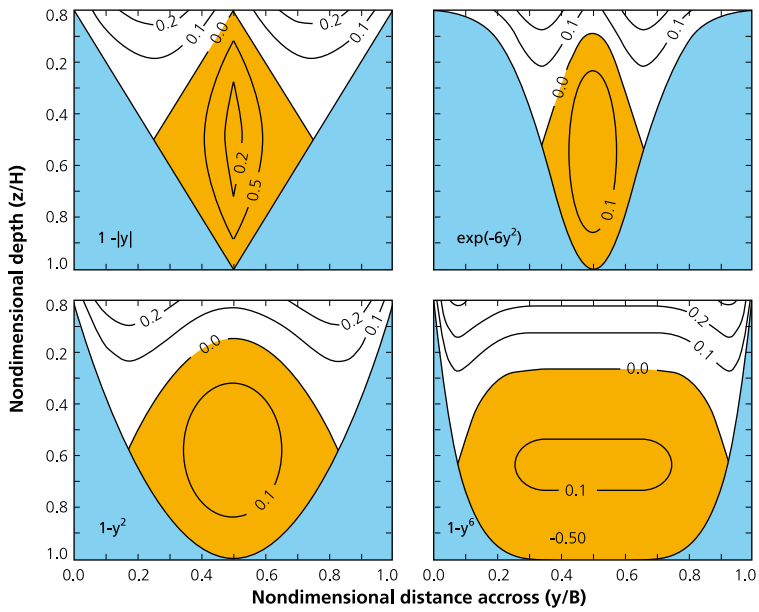
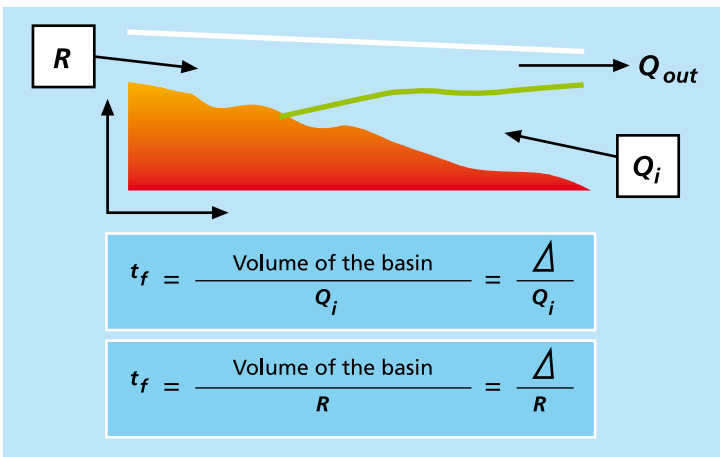


FIGURE 8
An illustration of the concept of flushing time

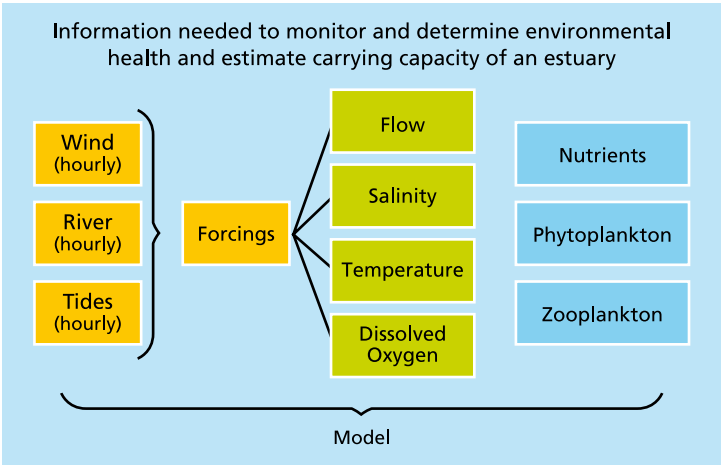


Flushing times and carrying capacity

The circulation in estuarine systems results from the complex interplay among river discharge, tides, winds, earth's rotation and bathymetry. Elucidation of such complex interplay is necessary to accurately determine the capacity of estuarine systems to flush and ultimately to assess the carrying capacity of a basin. There are different ways to estimate and define the time required to renew the waters of an estuary as outlined by Sheldon and Alber (2002; 2006) and Lucas (2010). There are actually concepts related to *turnover* or *flushing time*, *residence time*, water *age*, and *transit time*. Each of these concepts describes distinct processes that effect water or material (dissolved or suspended) renewal in an estuary.

Flushing time or turnover time t_f is the time required to replace the volume of a basin Δ typically by the volume inflow Q_i associated with the gravitational circulation, i.e. $t_f = \Delta / Q_i$ (Figure 9). This approach requires reliable quantification of net volume inflow into the basin. For dissolved or suspended matter, the flushing time will be given

FIGURE 9
An illustration of the concept of flushing time



by the ratio of the total mass of dissolved or suspended matter M throughout the basin to the flux F of mass M through the basin, i.e. $t_f = M / F$. An alternative definition of flushing time takes into account the river volume discharge R, instead of the volume inflow from the ocean Q_i, i.e. $t_f = \Delta / R$. Yet another definition calculates flushing time from the volume of fresh water in the basin Δ_f, where $\Delta_f = \Delta(S_o - S_m)/S_o$ and S_o and S_m are the ocean salinity and the basin's average salinity, respectively. Thus, the alternative form of this turnover time estimate is $t_f = \Delta_f / R$. Any of the preceding definitions involve processes that will vary greatly for different tidal, wind and river discharge forcing conditions. Therefore, one value of flushing time does not appropriately represent actual conditions.

Additional definitions of flushing time explicitly include the effects of tides through the volume of the tidal prism Δ_p and the tidal period T_p. The tidal prism volume is the volume of water that enters a basin with every tidal cycle and equals the surface area of the basin times the tidal range. The turnover time then is given by $t_f = \Delta\ T_p / \Delta_p$. Note that the ratio Δ / Δ_p is the volumetric portion related to the tidal prism. In essence, this definition documents the number of tidal cycles required to flush the basin. Because Δ_p will also change from spring to neap tides, this approach will yield a range of values for flushing time.

Residence time is the time required for water or material elements found initially at certain locations of a basin to exit the basin. This concept is different from flushing time in the sense that flushing time represents one value, or a range of possible values, for the entire system. Residence time implies a space-dependent distribution for the same system. It is typically represented with contour maps obtained from numerical model results. These contour maps indicate the time it would take for a fluid or material element to leave the basin at all locations in the basin. Contour maps should be generated for different tidal phase releases of the fluid element and for various forcing conditions related to freshwater discharge and wind.

The age of an element of fluid is the time it has remained within a basin since the time it entered. Similarly to residence time, age depends on the location of the basin. Contour maps of age are typically generated with numerical models to yield a comprehensive representation of areas most prone to pollution. Combining maps of residence time and age yields *transit times* for particles or fluid elements throughout the basin.

It appears, from the descriptions of flushing, residence and transit times, that the best way to characterize regions with most sensitivity to water quality issues, e.g, regions of low oxygen or high nutrients, might be to use maps of residence and transit times. These maps will only be reliable if they are produced with a well-tested and carefully calibrated numerical model. Such a model can help in guiding the locations of aquaculture centres to take maximum advantage of the carrying capacity of the system. For instance, the model could predict threshold values for transit times, nutrients and dissolved oxygen that cannot be exceeded in order to maintain aquaculture activities sustainable, thus optimizing the system's carrying capacity.

Numerical model – basic information required

Another suggestion of this paper is that in order to optimize the carrying capacity of a basin, a bullet-proof numerical model is required to help in the decision-making. The development of such a bullet-proof model is titanic, given the natural variability of a coastal basin. Model development and implementation shall involve three basic stages. 1) Carry out studies to determine the spatial structure and temporal variability of circulation and mass distributions in the basin. This stage will allow better understanding of the system. 2) Develop, calibrate and validate a numerical model that reliably represents actual environmental conditions. This stage will allow emulation of the system. 3) Use the model to determine different scenarios related to aquaculture sites and size of production, and find the optimal number and location for those sites. This stage will allow making decisions about the system. Each one of these stages involves an extremely challenging set of activities. Thus, each one of the 3 proposed stages should be developed sequentially because of the strong dependence of stage 2 on stage 1 and of stage 3 on stage 2. Maybe stages 2 and 3 can be started before stage 1 is completed, but reliable results will only be obtained with the successful completion of the previous stage.

The first stage, carry out studies to determine the spatial structure and temporal variability of circulation and mass distributions in the basin, shall entail field studies and numerical model simulations. Field studies shall involve measurement of the main forcings that drive and shape the system, namely wind velocity, river discharge, tidal forcing and bathymetry (Figure 9). These are essential variables needed to understand and model the system. Other essential variables that need to be measured to understand and model the system are hydrographic: currents, temperature, salinity and dissolved oxygen. These variables can be measured routinely and should be sampled at high spatial and temporal resolutions. High spatial resolutions can be achieved with surveys that collect underway data, while high temporal resolutions can be attained with mooring deployments. Other challenging variables to measure are biochemical: phytoplankton, zooplankton, nutrients, oxygen demand in the water column and in the sediments. These biochemical variables are quite important but cannot yet be measured reliably with the same temporal and spatial resolution as hydrographic variables; the technology is almost there, however. Part of the first stage should also be the development of a numerical model of the system to carry out process-oriented studies to better understand the information provided by the field surveys. This model will be the first step toward the second stage.

The second stage of developing a model to determine carrying capacity and siting of aquaculture activities consists of development, calibration and validation a numerical model that reliably represents actual environmental conditions. This three-dimensional model should use the main forcings assessed from stage 1 to try to represent the flow and hydrographic conditions observed. There are a good number of numerical models, already developed, that simulate the hydrodynamics and some water quality aspects in coastal environments. It will be a matter of personal option and/or expertize with a particular model the deciding factor of which one to choose for implementation at the basin. This stage can be arduous because of the multiple parameters that need to be tuned for the model to produce acceptable results. A quantitative measure of the quality of the numerical model results should be implemented to decide when the next stage can be started.

The third stage will consist of using the model to determine different scenarios related to aquaculture sites and size of production, and find the optimal number and location for those sites. This stage is the bottom line of the activities and could be developed in operational mode in such a way that the addition of new sites can be evaluated effectively. This stage will simulate, at the very least, the impact of number and location of aquaculture sites on the concentration of dissolved oxygen. This will be

one way of determining the carrying capacity of the study basin. Additional variables to simulate could include nutrients, phytoplankton and zooplankton, involving a marked increase effort to achieve it.

The 3 stages proposed above are quite elaborate. In many cases, the development of the three-stage approach might be unfeasible or unrealistic. For rapid and simple diagnostics a few other tools could be used. For instance, on the basis of the physical concepts discussed throughout this document one can use criteria to determine whether one side of the basin is more prone to flush water seaward or not. These criteria are presented next, as well as a simple criterion to determine an area of influence of a cage or cluster of cages.

Simple criteria to determine whether flow is different across the basin

In essence, two simultaneous criteria can be used to determine whether lateral variations in hydrography and flow are expected to be relevant in a semi enclosed system, i.e. whether it would make a difference to locate a cage on one side of the basin or the other. The first criterion can be given by the ratio of internal Rossby radius to width of the system W. If this ratio, which is also known as the Kelvin number K_e is greater than 0.25, it is likely that lateral variations will appear because the earth's rotation will cause a long-term lateral segregation of inflows and outflows (Valle-Levinson, 2008).

The second criterion is the Ekman number E_k, which equals A_z, the eddy viscosity (m^2/s), over the product of Coriolis parameter f and H^2 where H is the maximum depth of the cross-section:

$$E_k = \frac{A_z}{fH^2}$$

Taking A_z of 0.001 m^2/s as a typical value and f as 0.0001 s^{-1}, E_k could be simplified to $10H^{-2}$. If $E_k > 0.001$ it is likely that some lateral variations will appear because of bathymetric and frictional effects (Valle-Levinson, 2008). It is then proposed here that when both $\boldsymbol{K_e < 0.25}$ **and** $\boldsymbol{E_k < 0.001}$, then it would likely make very little difference across the basin to locate aquaculture activities on one side of the basin, relative to the other.

Simple criterion for separation of clusters of aquaculture facilities or cages

For cases when an elaborate approach to determine siting and carrying capacity (as that outlined in the Numerical Model section) is unfeasible, a simple approach centred on the tidal excursion at the site can be used to optimize the distance between contiguous facilities. The tidal excursion is the distance a suspended or dissolved material would travel throughout one half tidal cycle (throughout flood tidal flow or throughout ebb tidal flow). For this approach, two tidal excursion length scales need to be determined: the along-basin tidal excursion D_x and the across-basin tidal excursion D_y:

$$D_x = \frac{U_0 T}{\pi}; \quad D_y = \frac{V_0 T}{\pi}$$

where T is the dominant tidal period in seconds and U_0 and V_0 are the maximum along-basin current and across-basin current, respectively. These expressions are obtained from the integration of a sinusoid motion over half its cycle. The expressions can also be used for elucidating the area of influence of wind-driven currents for winds with period T. Note that for a semidiurnal tide (T = 44712 s or 12.42 hrs), a tidal current of 1 m/s yields an excursion D_x of ~14 km, which should be the minimum distance between clusters or cages in a basin with those characteristics. This distance would ensure that the interaction between dissolved and suspended material from different sites is minimized.

The values of D_x and D_y can be used to draw "ellipses of influence," or areas of influence, of each site or cluster (Figure 10). The ellipse of influence coordinates e_x, e_y are given by:

$$e_x = D_x \cos\Phi \cos\omega t - D_y \sin\Phi \sin\omega t$$

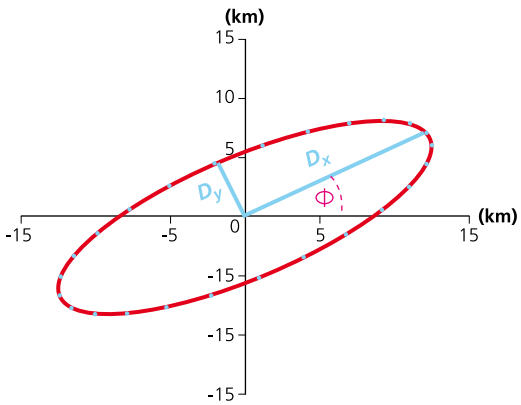
$$e_y = D_x \sin\Phi \cos\omega t + D_y \cos\Phi \sin\omega t$$

where Φ is the preferred or predominant direction of the current (degrees from East; could be zero if there is no preferred direction), ω is the frequency of the tide ($2\pi/T$) and t is time at appropriate intervals between 0 and T. These ellipses of influence may be used to represent areas of potential deleterious effects of a site on a neighbouring cluster. The information needed to generate the ellipses is: a) main direction of tidal currents (principal-axis direction) Φ; b) tidal current amplitude (maximum strength) in the main direction U_0; c) tidal current amplitude in the direction perpendicular to Φ, i.e. V_0; predominant period of the tide T; and the maximum displacements in the along-basin and across basin directions, i.e. D_x and D_y.

Summary and recommendations

In order to allow coastal aquaculture activities to be sustainable in a given basin, a three-stage process is proposed. This process should eventually allow determination of carrying capacity of the basin and optimal location of facilities. All stages of the process that leads to sustainability of aquaculture in a basin would involve the study of the basin through a combination of field measurements and numerical model implementation, calibration and validation. Basic forcing agents that need to be considered in the study are freshwater discharge (and its seasonal variability), atmospheric forcing (with its synoptic and seasonal variability), tidal forcing (with semidiurnal, fortnightly and seasonal variability), bathymetric effects and earth's rotation effects. These forcing agents would determine temporal and spatial variations of relevant parameters, such as hydrography, dissolved oxygen, and nutrients. Each of the stages proposed would allow understanding of, emulation of, and decision-making in the basin.

FIGURE 10
Ellipse of influence showing the main parameters that define it. In this case, Dx is 14 km, Dy is 5 km and is 30 degrees. The center of a cage would be located at (0, 0)



More easily applicable recommendations have to do with the location of neighbouring cage clusters on the basis of the "ellipse of influence." Also, two criteria based on non-dimensional numbers are proposed to be applied simultaneously in order to determine whether it would make any difference to locate clusters on either side of a channel-like basin.

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Regional Reviews

Environmental interactions and initiatives on site selection and carrying capacity estimation for fish farming in the Mediterranean

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Abstract

During the past two decades fish farming in the Mediterranean has increased very rapidly particularly in the coastal zone of the Northern part of the basin particularly through the farming of sea bream and sea bass. A series of national and, particularly, EU-funded research projects have addressed complementary aspects of the issue of environmental interactions of aquaculture in the Mediterranean since 1995. These included *inter alia* benthic and pelagic effects, modelling, interactions with fisheries, seagrasses, socio-economic issues etc. This background knowledge now makes possible the attempt to harmonize the regulation of aquaculture among all Mediterranean countries. A series of such initiatives is presented regarding the modernization of the regulatory framework of Aquaculture in the Hellenic Republic and the attempt by the GFCM (General Fisheries Commission for the Mediterranean) to define common environmental standards for site selection and carrying capacity of coastal aquaculture.

Introduction

Duarte *et al.* (2009) have estimated that aquaculture will have to increase production substantially during the forthcoming decades to increase animal protein supply to the increasing human population. Therefore, it is likely that some of the coastal and shelf ecosystems and particularly those that are suitable for aquaculture developments will face environmental pressures significantly higher than those they have experienced so far. In this context the assessment of the carrying/holding capacity of a receiving environment with respect to aquaculture production and consequently the adoption of good practices and sound environmental regulations is an indispensable prerequisite for the sustainability of aquaculture and the food production sector in general.

In the Mediterranean aquaculture and particularly fish farming has increased almost exponentially during the past 3 decades mainly with seabream (*Sparus aurata*) and seabass (*Dicentrarchus labrax*) farming in sea cages. Some new to aquaculture species have been used successfully for cage farming as well but their overall percentage in

the total production figures is still quite small. The Hellenic Republic is the leading producer country in the Mediterranean followed by the Republic of Turkey, the Kingdom of Spain and the Republic of Italy but gradually in all Mediterranean countries the production increases. After 2000 tuna farming has also emerged in various Mediterranean countries mainly the Kingdom of Spain, the Republic of Croatia, the Republic of Malta and the Republic of Cyprus and recently also the Hellenic Republic and the Republic of Turkey.

Mediterranean is a unique marine ecosystem with some specific environmental attributes affecting aquaculture: (a) high temperature in the water column (minimal temperature of 12°C reaching up to 25°C during summer) favouring rapid growth of fish and allowing production throughout the year, (b) microtidal regime (<50 cm in most places) reducing the dispersion and of dissolved and particulate wastes of fish farms and the water renewal in enclosed bays with weak currents, (c) oligotrophic conditions (with a few exceptions such as the Adriatic and some specific bays with riverine inputs), with low concentration of nutrients, primary productivity, low phytoplankton biomass, and relatively low quantities of particulate organic material and high levels of oxygen. These conditions are favourable for fish farming, allowing low stress for the farmed stock but not very suitable for mussel farming, (d) unlike other ocean systems, the limiting factor for primary productivity is Phosphorus rather than Nitrogen and therefore eutrophication (even locally) may occur only if P is released in adequate quantities, (e) rich marine fauna and flora particularly in the coastal zone, with a high percentage of endemic species. However, both abundance and biomass of most ecosystem components are rather low due to oligotrophic conditions.

This waterbody is shared by 21 countries with different cultural traditions, economic structure, societal profiles and legislative frameworks. The Mediterranean history is rich in collaboration traditions but also in conflicts. In other words the Mediterranean is a miniature of the world and therefore a strategy aiming at multinational cooperation, exchange of information and harmonization of regulations which becomes successful here it is likely to be viable also in any other region of the world.

This is why FAO, GFCM have promoted initiatives to assist cooperation for the development of aquaculture, to enhance the dialogue among Mediterranean states and stakeholders regarding three main issues i.e. site selection and carrying capacity, sustainability indicators and marketing of aquaculture products. In this review, we will refer to the work carried out in the framework of the Working group on site selection and carrying capacity (WGSC) and the associated project SHoCMed (Siting and Holding Capacity in the Mediterranean) which is co-funded by the EU and the GFCM.

Environmental interactions of aquaculture in the Mediterranean

During the past 15 years a series of national and EU funded research projects have addressed the issue of environmental interactions of aquaculture in the Mediterranean exclusively or in a broader framework. I could mention a few ones here: **MERAMED** (Development of monitoring guidelines and modelling tools for environmental effects from Mediterranean aquaculture) designed to provide a specific model (MERAMOD) for the benthic effects of fish farming in the Mediterranean and to address a series of hypotheses relating to environmental effects and monitoring; **MedVeg** (Effects of nutrient release from Mediterranean fish farms on benthic vegetation in coastal ecosystems), carried out in 4 Mediterranean countries (the Kingdom of Spain, the Republic of Italy, the Hellenic Republic, the Republic of Cyprus) and focusing on the effects of fish farming on *Posidonia oceanica* meadows; **AQCESS** (Aquaculture and Coastal Economic and Social Sustainability) which has examined both environmental and socio-economic aspects of the aquaculture performance in Europe analyzing conflicts of uses, labour mobility as well as large-scale effects of aquaculture zones; **BIOFAQs** (BIOFiltration and Aquaculture: an Evaluation of Substrate Deployment

Performance with Mariculture Developments), which carried out research on the potential for use floating biofilters as a means for mitigation of aquaculture impacts on the water column; **SAMI** EU FP6 project (Synthesis of Aquaculture and Marine Ecosystems Interactions) which provided a synthesis of the above projects in EU-FP5 incorporating also other issues such as the shortage of fish meal and fish oil and the potential ecological risks from the pressures on marine ecosystems; the **ECASA** EU FP6 project (Ecosystem approach for sustainable aquaculture) which involved 16 research partners (8 from the Mediterranean) from 13 member states. The outcome of this project is the most up-to-date toolbox of environmental models related to aquaculture and an extensive list of indicators that have been developed by a large number of experts and have been discussed with various stakeholders in Europe; the ongoing **SPICOSA** EU FP6 project, (Science and policy integration for coastal system assessment) has also a Mediterranean and a fish farming component and is likely to be of some interest when it is completed; the **PREVENT-ESCAPE** project: (www.sintef.no/Home/Marine/Fisheries-and-Aquaculture/Aquaculture-Technology/Aquaculture-constructions/Prevent-Escape/) a new EU FP7 project which started last year addressing the environmental impacts of fish escaping from fish farms and proposing mitigation measures. Almost half of the scientific effort will be used to address this issue in the Mediterranean.

As a consequence of this research activity, during this period there has been a significant increase in the amount and quality of the published information on aquaculture-environment interactions in the Mediterranean (see reports by Soto and Crosetti, 2005 and Karakassis and Angel, 2008). Most of these papers published in the prime scientific literature, focused on fish farming and ca 25 percent on shellfish. Most of the papers (>80) were related to benthic processes typically with geochemical variables and macrofauna or meiofauna, some (>30) focusing on nutrients and/or plankton, effects on *Posidonia* meadows (>25) and interactions with wild fish (19).

Investigations on the water column in the vicinity of Mediterranean fish farms, there was little observed increase in Chla content (Pitta *et al.*, 1999; La Rosa *et al.*, 2002; Pitta *et al.*, 2005) as was also the case in other surveys in the vicinity of fish farms in other parts of the world (Nordvarg and Johansson, 2002; Soto and Norambuena, 2004). This was despite the continuous nutrient supply which is known to be discharged from fish farming activity (Karakassis, Pitta and Krom, 2005 and references therein). A recent study by Dalsgaard and Krause-Jensen (2006) using macroalgal and phytoplankton bioassays revealed a high primary productivity near the fish cages rapidly decreasing with distance from the farms. The experiment with dialysis bags was repeated using filtered and unfiltered seawater (Pitta *et al.*, 2009) and showed that grazing played an important role in the regulation of phytoplankton communities, which is also compatible with the findings of Thingstad *et al.* (2005) regarding P addition as well as with the findings of Machias *et al.* (2004, 2005, 2006) regarding the rapid transfer of nutrients up the food web.

Sediment anoxia, patches of *Beggiatoa* and absence of macrofauna have been reported in relation to salmon farming in the North Atlantic (Rosenthal and Rangeley, 1988; Hansen, Pittman and Ervik, 1991) and the Baltic Sea (Holmer and Kristensen, 1992). Despite the microtidal regime of the Mediterranean, none of the studies carried out in fish farms in this area showed an azoic zone, in terms of macrofauna, in the close vicinity or even beneath the cages (e.g. Karakassis *et al.*, 2000; Tomassetti and Porrello, 2005; Klaoudatos *et al.*, 2006; Yucel-Gier, Kucuksezgin and Kocak, 2007; Dimitriadis and Koutsoubas, 2008). Furthermore, Maldonado *et al.* (2005) showed that in 5 semi-offshore farms in the Kingdom of Spain the effects on benthic macroinvertebrate communities were even less possible to detect finding no substantial differences between farm and control sites. In most cases the effects of fish farming on macrobenthic diversity and community structure were detectable and compatible with the Pearson

and Rosenberg (1978) empirical model up to a distance of 10–25m from the edge of the cages. Regarding the Water framework Directive of the EU data from Aguado-Giménez *et al.* (2006) from the Kingdom of Spain and Karakassis *et al.* (unpublished) from the Hellenic Republic indicate that the benthic quality directly beneath fish farms cannot be considered as "High" or "Good" no matter what index is used.

Underwater diving census and video surveys beneath fish farms in the Western and Eastern Mediterranean (Dempster *et al*., 2002; Smith *et al.*, 2003; Vega Fernandez *et al.*, 2003; Golani, 2003) confirmed that large numbers of a diverse fish fauna are aggregated under the fish cages during feed supply. Tuya *et al.* (2006) showed that this aggregation was related to the feed supply rather than to FAD-effect since their densities approach "normal" densities after the cessation of fish farming. Dempster *et al.* (2002) have shown that the abundance, biomass and species richness of the aggregating fish assemblages are negatively correlated to distance from shore and positively with the size of the farm. These authors suggest that coastal cage fish farms may act as small pelagic marine protected areas (MPAs). Vita *et al.* (2004) conducted field experiments with sediment traps and concluded that 80 percent of the particulate OM leaving the rearing net-pens may be consumed before settling on the seabed and they have attributed a large part of this consumption to the wild fish aggregating beneath the farms. Fernandez-Jover *et al.* (2007) have found that the wild fish associated with fish farms had significantly higher fat content than the control fish in the area and therefore there is some potential for increase in their spawning ability particularly if they are also protected from fishing.

Investigations in the Eastern Mediterranean basin have addressed the issue of interactions with wild fish at larger spatial scales i.e. beyond the FAD effect. Machias *et al.* (2004) have shown that fish densities in a coastal bay in the Aegean Sea where a fish farming zone is established now are higher by a factor of two in comparison to those recorded in 1987 i.e. before the onset of fish farming in that area. Also Machias *et al.* (2005) using experimental trawling in 3 fish farming zones in the Aegean have shown that the abundance biomass and diversity of demersal fish was significantly higher than at the respective control areas. Also time series analysis of commercial fisheries landings in areas with and without fish farming (Machias *et al.*, 2006) showed a sudden increase in landing biomass after the onset of aquaculture in the fish farming zones. These authors have attributed these changes in a shift of primary production coupled with a rapid transfer of dissolved waste nutrients up the food web in a nutrient-starving oligotrophic system.

Posidonia oceanica is a slow-growing endemic seagrass species of the Mediterranean thriving in clear oligotrophic waters with high transparency (Holmer, Perez and Duarte, 2003) providing important ecosystem services such as shelter to juvenile stages of various marine species, protection against sediment erosion and carbon sequestration thereby reducing CO2 fluxes towards the atmosphere. The recovery times of *P. oceanica* meadows when damaged are very long, in the order of centuries, and losses of this species are thus considered to be irreversible at managerial time scales. The good water quality required by *Posidonia* makes its' habitat "ideal" for fish farming as well and therefore there are fears that a large proportion of fish farming activity is sited above such meadows despite the existing regulations in most Mediterranean countries. Research results during the past 10 years have provided information on the mechanisms of environmental deterioration related to the loss of Posidonia sites and the spatiotemporal scales of the processes involved. A synthesis paper of the MedVeg project (Holmer *et al.*, 2008) has examined a series of drivers of seagrass decline due to fish farming effects and identified the sedimentation of waste particles in the farm vicinity as the main driver of benthic deterioration. Holmer *et al.* (2008) have recommended a safety distance of 400m for management of *P. oceanica* near fish farms followed by establishment of permanent seagrass plots samples annually for monitoring the health of the meadows.

Carrying capacity and fish farming

In general carrying capacity is a well defined concept in Ecology i.e. "the maximum population size a certain environment can support for an extended period of time, for a population of a particular species". The fact that there is increasing demand for estimating carrying capacity by various stakeholders including regulators and farmers is a positive sign indicating that it has become understood that aquaculture growth (like most other types of development) has an upper limit. This concept is readily applicable in the case of e.g. mussel farming where the farmed stock directly depends on the availability of plankton resources in the ambient water.

However, in the case of cage fish farming, the farmed stock depends on allochthonous food sources, and therefore the availability of food, as well as that of space and water may be practically limitless. Oxygen availability could be a problem determining carrying capacity in cases where water renewal is rather limited. However, for reasonable densities no oxygen problem at the surface water layers has been recorded either in the literature or in the data we have looked at. Even though theoretically a problem of anoxia in the bottom in extreme cases of organic enrichment, it would be reasonable to stop/reduce farming before reaching this point.

It is therefore needed to determine carrying capacity based on environmental criteria, i.e. by adjusting the levels of production so as not to cause unacceptable environmental change. In this case there is obviously a need to define what is "not acceptable and of course this process includes political decision grounded on value judgments on what should be protected and to what extent. In other words, we must answer the critical question "How much environmental degradation can be tolerated before taking action for the suspension or restriction of the root cause?". Certainly, the environmental impacts vary depending on the particular characteristics of the recipient site, i.e. the variables defining the assimilative capacity of the system, as well as depending on the management practices of a farm, especially with regard to the (unintentional) food wastage (which affects the conversion ratio, FCR, and the economic efficiency of the farm) or limiting escapes but also in relation to care for less environmentally damaging, but certainly unacceptable, effects such as dispersion in the area around the site of solid (plastic) packages from fish feed.

For bivalve farming McKindsey *et al.* (2006) have defined four types of carrying capacity among which "ecological carrying capacity: the stocking or farm density which causes unacceptable ecological impacts". In this context the establishment of a threshold should the point beyond which ecological change becomes unacceptable. Groffman *et al.* (2006) have identified ecological threshold as the point at which there is an abrupt change in an ecosystem quality, property or phenomenon, or where small changes in an environmental driver produce large responses in the ecosystem. On the other hand thresholds may also be defined in a legal framework as the point beyond which pollution load becomes unacceptable. This threshold defines the legal boundary between acceptable contamination and unacceptable pollution (Hassan, 2006).

In this context, Environmental Quality Standards and environmental thresholds become the major prerequisite for estimating the carrying capacity of a fish farm in a given site and also necessary for a meaningful environmental impact assessment and environmental monitoring.

The Greek regulatory approach to adaptation of production to carrying capacity

In the Hellenic Republic the legislation on aquaculture requires an EIA before a licence is given and consensus is needed by 6 major agencies (Ministry of Agricultural Development and Food, Ministry for the Environment, Navy, Archaeology, Ministry of the Merchant marine, GR Tourism Organization). The content of the EIA was relatively unclear and the overall scheme was very inflexible allowing 150 tonnes of production per 10 000 m^2, regardless of the characteristics of the site.

A new regulation since 12/06/09 (common ministerial decision by Ministry of Environment and Ministry of Agricultural Development and Food) based on a study carried out by Univ. of Crete aiming at providing a means to adapt production levels to the environmental characteristics of the receiving environment. The Production level is defined by the formula:

$$\Delta = [150 + 8(E-10)]\ fA\ fB\ fK$$

Where, E = area of the farm site (in 103 m2), fA = distance coefficient, fB = depth coefficient and fK = exposure or current coefficient.

The fA, fB and FK coefficients have different values depending on the characteristics of the site. E.g. the distance from shore coefficient (fA) for distance <100m becomes 1.00, for 101–400m it is 1.25, for 401–1000m it is 1.50 and for >1000m it is 2.00.

These values were determined through a Delphi exercise after asking 31 experts from 20 countries. According to the new regulation:

- Distance between farms should be >500m
- The leased marine area should be 10–100 thousand m^2
- Depth >18m and at least 2 times the depth of the nets
- Loading per m^3 is provided for different species and size of fish
- Mortality (bream-bass) should be <17 percent and for other Med spp <30 percent
- No new farms on Posidonia meadows
- No expansion of the capacity of the ones over Posidonia beds
- The existing ones will not be renewed after the expiration of their concession

The overall project for the development of the new system comprised the following elements:

- Bibliographic analysis for existing standards in other countries, environmental impacts and regulatory schemes.
- Analysis of benthic data from 11 farms in the Hellenic Republic, some of which had exceeded the production they were licensed for.
- Delphi exercise with experts which resulted in 3 scenarios (conservative, intermediate and expensive) using different percentiles in the experts' responses.
- Proposal for a new system, including most of the above points.
- External evaluation by 5 international experts who participated in the workshop with the stakeholders
- A workshop involving >70 representatives of stakeholders plus the external evaluation committee where the overall scheme was discussed
- The external evaluation committee submitted a report and discussed details in an additional workshop
- The Proposal was revised to accommodate suggestions by the reviewers
- A ministerial decision Political decision was signed (ca 2 years later)

Although the above framework does not include a unique estimate/figure for the carrying or holding capacity eventually provides incentives (increase in licensed production) for the selection of sites which are likely to be more environmentally sustainable than those used so far.

The SHoCMed approach to site selection and carrying capacity

The objectives of the WGSC of the GFCM and the SHoCMed project are:

- To produce criteria for enhancing the integration of aquaculture in CZM by improving site selection and holding capacity standards.
- To provide a basis for harmonization of standards across the Mediterranean as a means for ensuring equal terms of market competition and minimal environmental damage.
- To know what are the consequences on site selection and holding capacity under a shift in production scale in Aquaculture which is likely to occur in the near future.

- To explore the potential for using Allocated Zones for Aquaculture (AZA) as a means for improving management for aquaculture aiming at (a) increase in production, (b) reducing conflicts and (c) reducing environmental impacts.

To this end, a series of actions have been used to address the issues of site selection and carrying capacity in the Mediterranean such as:

- Reviews of the existing bibliography on environmental impacts in the Mediterranean and establishment of a bibliographic database
- Review of legislative frameworks in the Mediterranean countries regarding site selection, licensing, environmental monitoring requirements and carrying capacity issues.
- Workshop on allocated zones for aquaculture (AZAs) as a site management tool
- Workshop on Environmental Quality Standards and a Delphi exercise to determine thresholds at each variable.

Among the conclusions in the documents of this working group there some points relevant to the present workshop:

- The WGSC suggested that both the lack of EQSs and the variability of monitoring practices leave the aquaculture industry exposed to accusations on responsibility for environmental degradation during conflicts with other users and interests in the coastal zone. Therefore the WGSC has emphasized the need for establishing not only criteria for site selection but also EQSs agreed between the regulators and all the stakeholders in the coastal zone.
- The adoption of the WFD by EU countries implies that by 2015 all coastal areas including those where fish farms are currently established will comply with a set of five-level standards reaching at least the level "Good". This scheme is unlikely to be compatible with cage aquaculture as has been shown by many different studies. The adoption of the AZE (allowable zone of effects or mixing zone) concept used e.g. by SEPA in the immediate vicinity of the farms is a useful tool for addressing the issue of environmental protection in a realistic way.
- The use of a common monitoring scheme for a certain period (long-term monitoring) will allow the assessment of its robustness through a future environmental audit which will result in a further improvement of it efficiency.
- The establishment of EQSs will improve the EIA process since it will allow predictions against predefined and known criteria thus increasing consistency in the licensing and monitoring procedures and increasing transparency in the relations between farmers and regulators.
- The WGSC has discussed also other needs for monitoring that need to be addressed in the final proposal including (a) differences between offshore and coastal aquaculture sites, (b) particular extra environmental variables that have to be monitored in specific types of farming (e.g. tuna), (c) different number of variables and/or frequency of monitoring depending on farm size and/or sensitivity of the receiving environment, (d) specific measures for monitoring AZAs and (e) availability of information regarding the effects of the environment and other activities on aquaculture.

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Aquaculture site selection and carrying capacity for inland and coastal aquaculture in Northern Europe

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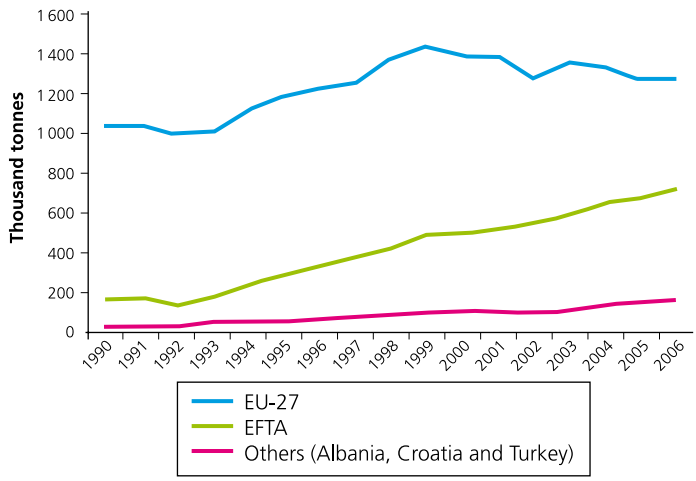
Abstract

European aquaculture has increased over the past 15 years primarily due to increased production in the Kingdom of Norway and the Republic of Iceland. While mariculture of finfish continues to grow (mainly of Atlantic salmon, sea bass and sea bream), production of molluscs and freshwater fish has shown a steady decline over recent years. Nevertheless Europe has a number of key strengths in aquaculture. There is a strong focus on technology and research, highly trained employees, and appropriate climate for many of the species currently in demand by consumers. Increasing demands on both coastal and inland environments have lead to increased competition with other activities for space and water, such as housing and tourism. This paper addresses issues relevant for site selection and carrying capacity for inland and coastal waterbodies in Northern Europe. In Northern Europe the development of aquaculture has focused primarily on intensive farming of carnivorous fish species mainly due to competition for land and water. Many of the factors to be considered depend on the culture system for example cage culture depends on water depth, water quality, water currents whereas land-based systems have to consider factors including water availability and quality, topography, and soil type. The degree of local impact is dependent on production scale and culture system, in addition to local and regional hydrodynamics and chemical characteristics.

Introduction

European aquaculture production has increased over the past 15 years as shown (Figure 1). However, production in the European Union (EU) has been more or less constant since 2000 whereas global aquaculture production has grown by one third. While the farming of sea fish continues to grow (largely due to three species – Atlantic salmon, sea bass and sea bream), production of molluscs and freshwater fish has shown a steady decline over recent years. Aquaculture in the EU contributes about

FIGURE 1
Annual European aquaculture production by major area



Source: European Environment Agency. www.eea.europa.eu

20 percent of the EU fish production, yet represents only 2 percent of global aquaculture production. The EU aquaculture sector directly employs approximately 65 000 people (EC Factsheet).

Europe has a number of key strengths in aquaculture. There is a strong focus on technology and research, highly trained employees, and appropriate climate for many of the species currently in demand by consumers. The quality standards set in Europe are rigorous to ensure that aquaculture products are healthy for the consumer, while sustainable with regards to the environment. These strengths also bring with them challenges. High standards inevitably result in higher costs which in turn has a negative impact on the ability to compete in national and international markets. Increasing demands on both coastal and inland environments lead to increased competition with other activities for space and water, such as housing and tourism. The following sections will address issues relevant for site selection and carrying capacity for inland and coastal waterbodies in Northern Europe.

Regional and national factors relevant to site selection for aquaculture

There are several aspects to be considered for the selection of a site for aquaculture depending on the species of interest and a host of other considerations, including socio-economic and political factors which will not be dealt with in detail here. In Northern Europe the development of aquaculture has focused primarily on intensive farming of carnivorous fish species mainly due to competition for land and water. It is widely recognized that this intensive development of the aquaculture industry has been accompanied by an increase in environmental impacts (Ervik *et al*., 1997). In this context, the sustainability of intensive mariculture has been brought into question (Read, Fernandes and Miller, 2001).

Many of the factors to be considered depend on the culture system for example cage culture depends on water depth, water quality, water currents whereas land-based systems have to consider factors including water availability and quality, topography, and soil type. The degree of local impact is dependent on production scale and culture system, in addition to local and regional hydrodynamics and chemical characteristics.

Inland waterbodies

Site selection and carrying capacity for inland aquaculture has many considerations to take, not least competition for use of water and land. Carp have historically been farmed in freshwater in Europe and Asia for thousands of years. The species appear to have been domesticated independently as the various types of farmed carp are native to different geographic regions, for example the Common Carp (*Cyprinus carpio*) originates in Central Europe. Carp and was an important food source in Western Europe in the Middle Ages, however due to the increase availability of other farmed

fish species such as Atlantic salmon (*Salmo salar*) and rainbow trout (*Oncorhynchus mykiss*) in addition to environmental constraints the importance of carp culture has declined. However, pond culture of carp is still a major form of aquaculture in Central and Eastern Europe. In Northern Europe there is limited farming in lakes and this is primarily rainbow trout.

In most European countries there are limited sources of freshwater available for the establishment of new fish farms, and further growth in aquaculture is expected to be in coastal regions and the open sea. The EU Water Framework Directive (WFD) was established in 2002 to protect and restore clean water across Europe and ensure its long-term, sustainable use (further details regarding the WFD are provided below). Site selection criteria are largely determined by the type of aquaculture considered: for example in extensive pond farming, factors include water resource availability, space and geomorphological- and geochemical factors. Water quality management criteria are a major issue defining the type of culture system which is feasible at a given site. Stocking density will be determined by the permit for extractable water volumes per unit time (set by the water authorities). Intensification methods for pond farming, such as is common for trout farming in several European countries, exist within the range of regulated effluent standards by using specifically designed system components such as concrete ponds, raceways, circular tanks, aeration, oxygenation, etc. The requirements to gain a license for aquaculture in freshwater systems varies among countries in Europe, however the WFD plays a central role.

Issues locally specific to species, cultures, and geographies

The Norwegian coastline is 21 000 km long, which is half the length of the equator, and the Kingdom of Norway has a population of approximately 4.9 million, eighty percent of which resides around the coast and up to 10 km inland. Consequently the Kingdom of Norway is greatly influenced by coastal culture, and engaged in marine economic development. There are three principle areas of interest in the coastal zone:

1. protection and conservation
2. recreation
3. usage

Conflicts arise between use and conservation, more specifically, between industry, recreation and nature conservation. The most important legal tool for integrated coastal zone planning is the Planning and Building Act of 1985, which was most recently amended in 2008. The intention of this Act is to harmonize planning of central-, county- and municipal activities. This covers area use and exploitation of natural resources assessed in conjunction with the municipals planning conditions. In the 100-metre belt along the seashore and river systems, special consideration shall be given to the natural and cultural environment, outdoor recreation, landscape and other elements of public interest (which prohibits most building in this zone). However the Act states that this prohibition does not apply where the municipality, in the land-use element of the municipal master plan, has permitted the erection of necessary buildings, small installations and storage facilities for use in agriculture, reindeer husbandry, fishing, aquaculture or sea traffic. There are 280 municipalities in the Kingdom of Norway which have the right to coastal planning of one nautical mile along their share of the coastline in close dialogue with the Norwegian Coastal Administration and the Directorate of Fisheries. The coastline is divided into different zones depending on the activities which are permitted in a particular region: traffic, fishing, aquaculture, nature and/or recreation. An area has to be assigned for aquaculture, or aquaculture and an additional activity in order to be able to establish a fish farm at a particular coastal site.

The Kingdom of Norway is currently the largest aquaculture producing country in Europe. The main aquaculture species in the Kingdom of Norway is Atlantic salmon (860 000 tonnes in 2009), followed by rainbow trout (76 000 tonnes in 2009), other marine fish species, mainly cod (*Gadus morhua*: 23 000 tonnes) and approximately 1 600 tonnes blue mussels (*Mytilus edulis*). Details regarding the integration of aquaculture approaches in the Kingdom of Norway with regulation and governance are provided in detail below.

In the Kingdom of Denmark the main aquaculture species is rainbow trout (approximately 90 percent in 2009, 37 000 tonnes trout production), followed by blue mussels and European eel, *Anguilla anguilla* (total aquaculture production 41 885 tonnes in 2009: Directorate of Fisheries, DK). The set of regulations for farming marine fish or shellfish depend on the type of aquaculture operation. Three categories are defined:

1. Land-based sea water farms taking in or pumping in sea water (including cooling water from for example power plants, the operation of the farm is dependent on the use of feed)
2. Farms with net cages placed in sea water, being defined as farms consisting of net cages/netted boxes or the like placed in marine waters. The operation of the farm is dependent on the use of feed.
3. Farms in seawater without the use of feed i.e. culture of bivalves like mussels and oysters

Before establishing or extending a farm a permit application must be completed according to regulations for polluting industries from the Ministry of Environment. Fish farming applications are submitted to the regional county and the Directorate of Fisheries who are both competent authorities able to issue a permit. The environmental regulation of fish farming in the Kingdom of Denmark started with the Environmental Protection Act of 1974, the Statutory Order of 1985 forbidding wet feed, and the Action Plan on the Aquatic Environment of 1987. In the case of freshwater fish farms, the latter was implemented through the measures stipulated in the 1989 Statutory Order on Fish Farms.

Extensive fish farming has been conducted in Sweden for hundreds of years, primarily pond culture of Common Carp (*Cyprinus carpio*) and Crucian Carp (*Carassius carassius*) In the 20th Century the comprehensive development of hydroelectric power plants was accompanied by the production and release of millions of Atlantic salmon and sea trout (*Salmo trutta trutta*) to compensate for the of loss of natural breeding habitats. At the same time there has been an increase in production and release of other naturally occurring or introduced stock such as the signal crayfish (*Pacifastacus leniusculus*) introduced from North America in 1969. In the 1980s there was an increase in the number and an intensification of fish farms primarily producing rainbow trout as well as an increase in blue mussel farms.

The Swedish Board of Fisheries is the government authority responsible for the conservation and exploitation of Sweden's fish resources. Aquaculture is economically a small industry in Sweden, but with a relatively large number of people involved. The licensing system is based on a given production volume per year, but in certain cases there are other requirements such as the maximum amount of feed used per year and maximum cage size. Fish production in freshwater represents approximately half of total Swedish production of farmed fish. There is some cage culture in a few big lakes such as Väneren, as well as in some large rivers with depths from 15–20 metres.

The yield of Swedish aquaculture in 2009 was 6 130 metric tonnes of fish for consumption and the dominant species was rainbow trout (6 413 tonnes in fresh weight), with 89 percent of the total production of fish for consumption. Furthermore there were 2 125 tonnes of blue mussels cultivated. The production of fish for release to the wild was estimated at 993 tonnes. The dominant species was rainbow trout

(651 tonnes), followed by brown trout (*Salmo trutta*: 212 tonnes) and Artic char (113 tonnes). For re-stocking approximately 2.9 million fry of Atlantic salmon and sea trout were released in 2009, mainly in rivers running into the Baltic (data source: Swedish Board of Fisheries and Statistics, Sweden, 2010).

As a result of existing strict regulations regarding discharges of nutrients from all activity in the Baltic Region, the potential for Swedish aquaculture is limited. This restricts both the expansion of production at existing locations, and the extension of aquaculture to new locations.

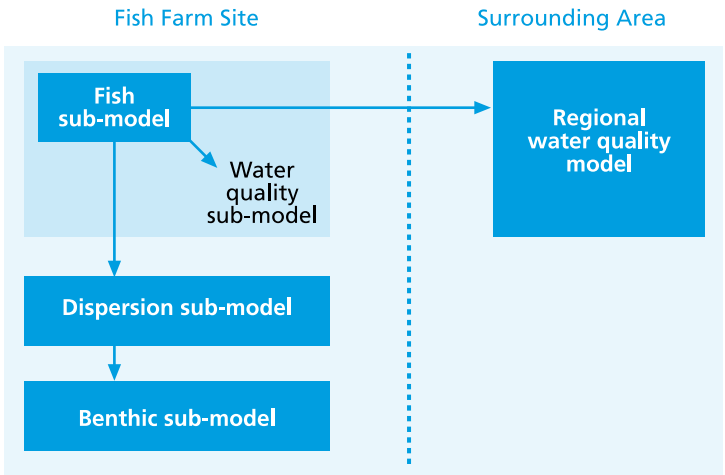
The Baltic Sea is one of the world's largest brackish water areas. It is a semi-enclosed sea with a surface area of 415 000 km^2 and a volume of 21 700 km^3, thereby representing 0.1 percent of the world's oceans in area, but only 0.002 percent of the volume (Ducrotoy and Elliott, 2008). Nearly all fish production in the Baltic Sea is rainbow trout (Finnish Environmental Institute, 2008) which are cultivated in net-pens. Total production of rainbow trout in the Baltic Sea in 2007 was 11 300 tonnes (Finnish Game and Fisheries Research Institute, 2008). Aquaculture causes relatively small-scale nutrient emissions, but local environmental impact may be considerable. Between 2004–2007, the input of nutrients to the system in the form of fish feed was 829 tonnes nitrogen/year and 115 tonnes phosphorous/year. Of the primary input, 70 percent was discharged to the Baltic Sea, directly from aquaculture and indirectly through waste management. The nutrient cycle could be closed partially by using local fish instead of imported fish in rainbow trout feed, thus reducing the net load of N and P to a fraction (Asmala and Saikku, 2010).

Use of models and decision support tools

Several tools exist to evaluate site selection for cage aquaculture, such as the model developed by Halide *et al.* (2009) which includes considerations of site classification, site selection, holding capacity and economic appraisal of farming at a given site. It is based on measurements of water and substrate qualities, hydrometeorology and socio-economic factors and classifies cage culture sites into one of three categories – poor, medium, and good.

In the Kingdom of Norway the Modelling-On growing fish farms-Monitoring (MOM), is the model legally required by the Directorate of Fisheries for site selection for mariculture of salmon and trout. The MOM model has been developed to estimate the holding capacity of sites for cage farming of fish (Stigebrandt *et al.*, 2004). The model comprises four sub-models (Figure 1), which are input parameters for one or more of the other sub-models. One advantage of a modular model is that the sub-models can be altered individually as new knowledge is acquired or as new managing procedures or fish species are introduced.

FIGURE 2
Overview of the MOM model system



Note: The local site model is linked to a regional (inshore) water quality model (Fjord Environment) (Aure and Stigebrandt, 1990). The output parameters from the fish sub-model are used as input parameters to the water quality sub-model, the dispersion sub-model and the regional water quality model. The dispersion sub-model delivers input parameters to the benthic sub-model.

The model management system MOM includes a monitoring program and Environmental Quality Standards (EQS) (Ervik *et al.*, 1997; Hansen *et al.*, 2001). In the MOM system the environmental objective for the management of sites for fish farming is that their impact must not exceed threshold levels that safeguard the well-being of both the fish and the environment. There are three basic environmental requirements which must be fulfilled in order to ensure long-term use of the sites:

1. The accumulation of organic material under and in the vicinity of the farms must not result in extinction of the benthic macro infauna. This condition is met if the flux of organic matter from the farm is adjusted to local dispersion and resuspension conditions so that the decomposition capacity of the benthic system is not exceeded.
2. The water quality in the net pens must meet the needs of the fish. This means that the concentration of oxygen is kept above a threshold level and that the concentration of ammonium and other potentially harmful substances are kept below threshold levels. These conditions can be met if the respiration of, and emissions from, the fish are adjusted to the rate of water renewal in the net pens.
3. The water quality in the areas surrounding the farm must not deteriorate. This requirement is fulfilled if the outlets of nutrients and organic matter from the farm do not contribute to significantly higher algae production in the surrounding surface water or result in low oxygen concentrations in deep water. When the environmental impact is being assessed the contributions of all other sources must also be taken into account, thus considering the total impact.

The holding capacity is determined from the lowest of the three estimates. The fulfilment of the first two requirements depends on local environmental parameters such as water depth, the annual temperature cycle and the vertical distribution of current properties, and concentrations of oxygen and ammonium. It also depends on the maximum fish density per unit area, so the physical configuration of the farm is of importance. These factors as well as feeding rate and feed composition are taken into account in the model. In practice, three different holding capacities are computed; one for each of the basic requirements. The holding capacity of the site is then given by the lowest of the estimates. For the model computations, site-specific environmental conditions such as water depth, current characteristics, concentrations of oxygen and ammonium and the annual temperature cycle must be known. The holding capacity will also depend on the size and the orientation of the net pens, as well as on the maximum fish density per unit area in the farm, the composition of the feed and the feeding rate.

Depending on the input variables the MOM system characterises a given location in terms of how suitable it is for locating a fish farm into the following categories:

A - Excellent
B - Very good
C - Good
D - Acceptable
E - Poor
F - Very poor

The MOM model system is primarily meant to estimate the holding capacity of new sites for fish farming, but it may also be used to assess the environmental consequences of changes in production on farms already in operation. The Ministry of Fisheries and Coastal Affairs is in the process of integrating the MOM system into a cohesive management system – MOLO (MOm–LOkalisering) (environmental monitoring – site selection) for mariculture.

Integration of current approaches with regulation and governance

Fish farming in coastal regions of the Kingdom of Norway is controlled by several laws and regulations administered by Authorities under the Ministry of Fisheries and Coastal Affairs, Ministry of Environment, Ministry of Agriculture and Food, with the Ministry of Fisheries as the main authority responsible for the industry. The Aquaculture Act introduced the licensing system in 1973, and initially imposed limitations on the maximum size of each farm, in addition to the maximum number of permits, which are issued by the Directorate of Fisheries. In 2005, the Aquaculture Act was amended and a new system was introduced for production restrictions with maximum permitted biomass (MTB) instead of a volume restriction of the sizes of fish farms, in addition to environmental monitoring. According to revised legislation, every 1 m^3 previously permitted farming volume is considered equal to 65 kg maximum biomass (with the exception of the regions Troms and Finmark where 1m^3 is considered equal to 75 kg biomass). An Act regarding environmental risk assessments of fish farms was enforced from June 2009. The maximum allowable biomass system combined with the requirement for environmental investigations for site selection and environmental monitoring during operation, aim to ensure environmentally sustainable production and protect fish health and welfare. In the event of applications for new farm licenses or expansion of existing facilities, environmental investigations of benthic conditions at the proposed site are mandatory, in addition to hydrographical and topographic surveys. During operation, fish farmers have to perform regular environmental monitoring of the benthic conditions at the site.

There are approximately 1000 permits for mariculture of Atlantic salmon and trout along the Norwegian Coast, one has to purchase a permit (from an existing owner), which has to be approved by the Directorate of Fisheries and then obtain a license to operate at a given site. In order to obtain a license, a form has to be completed, with relevant information regarding the site (water depth, current, water quality etc) and intended biomass, which is submitted to the Directorate of Fisheries, (in accordance with the Aquaculture Act), the Norwegian Food Safety Authority (in accordance with the Food Law), and the Climate and Pollution Agency (in accordance with the Pollution Act). The application is also open for public consultation, and takes considerable time to process. If a license is authorized by the Directorate of Fisheries (from 2011 by the County Authority) the farm has to be established within two year, and there are certain legal requirements which the fish farmer has to follow up. This includes a written operating plan, internal control and monthly reporting to the Directorate of Fisheries (feed use, number of fish, mortalities etc.).

The Directorate of Fisheries is responsible for the inspection of fish farms, which is conducted on a risk-basis. For example there is annual inspection of salmon and trout farms which are located in fjords which have significant wild salmon populations. No new locations for fish farming are being given in fjords with important wild salmon populations, and existing farms are being relocated further off the coast.

Obligatory monitoring of fish farms was introduced from the 1st of January 2005 according to the classification of the standard NS9410 B-survey, and mandatory reporting of the results to the Directorate of Fisheries from summer 2009. The B-survey includes several parameters and distinguishes between four conditions of benthic effect from 1, which represents little effect of the fish farm to 4 which is defined as overloaded. Details regarding the organic loading from different fish farm locations from the North to the South of the Kingdom of Norway are provided (Table 1). From a total of 996 locations, 332 locations were surveyed (Directorate of Fisheries, the Kingdom of Norway). Each fish farm has several locations which are used in rotation in addition to mandatory fallow periods. Consequently many of the locations will be without fish and are thus not surveyed until they are operational.

The recipient may also be monitored according to the more comprehensive C-survey of the NS-EN ISO 1666 standard in certain cases which includes a more detail examination of the benthos and distinguishes between four environmental states where condition 4 represents an overload to the extent that there are no animals present in the sediment.

Salmon hatcheries are freshwater aquaculture operations which mainly use tanks, and which typically have more complex legislative requirements than mariculture in pens or cages. The Norwegian Ministry of Fisheries and Ministry of Agriculture simplified legislation regarding hatcheries in an Act enforced from January 2001 regarding licensing-, establishment-, and management of hatcheries in addition to disease prevention. This Act reduced the number of legislative documents to be followed and facilitated the cooperation between the fisheries- and veterinary government agencies. This Management and Disease Act was adapted to the management- and disease challenges affecting the industry and includes several regulations which the industry have to adhere to.

Water is privately owned in the Kingdom of Norway so an applicant wishing to apply for a fish farm license which requires freshwater first has to obtain permission from the owner to extract the water. Approval of sites for establishing freshwater fish farms requires compliance with many laws and Public Authorities. Central Acts include the Aquaculture Act, Pollution Act, Planning- and Building Act, Food Law, and Water Resource Act, which are all dealt with by separate Authorities. It is essential that the process is coordinated and clarifications dealt with prior to a license being approved by the Directorate of Fisheries in accordance with the Fish farming Act. The Directorate of Fisheries, in collaboration with the Norwegian Food Safety Authority, the Norwegian Coastal Administration, the Climate and Pollution Agency and the Norwegian Water Resources and Energy Directorate has produced a guidance document for applications for freshwater aquaculture. The main type of freshwater aquaculture in the Kingdom of Norway is salmon and trout hatcheries. There are very seldom applications for new hatcheries most applications are to increase the size of existing hatcheries.

TABLE 1
Organic loading at fish farm locations in the Kingdom of Norway between 2008–2010 measured according to the NS 9410 B-survey where condition 1 is best (low impact) and condition 4 is overloaded.

County	Condition				Total no. of surveys	Total no. of locations
	1	2	3	4		
Finnmark	5	2	2	1	10	62
Troms	21	8	0	0	29	107
Nordland	48	19	6	1	74	197
N.-Trøndelag	15	5	2	0	22	71
S.-Trøndelag	8	4	2	0	14	80
Møre and Romsdal	26	3	2	0	31	105
Sogn and Fjordene	23	5	3	0	31	99
Hordaland	50	31	6	0	87	197
Rogaland	14	8	4	0	26	64
Agder	4	4	0	0	8	14
Total	214	89	27	2	332	996

Source: Directorate of Fisheries

There are approximately 220 salmonid hatcheries in the Kingdom of Norway, of which about 75 percent are flow-through systems taking freshwater from rivers, and discharging the water in to the sea or fjord. There are an increasing number of recirculation systems, which rely on partial recirculation of freshwater prior to discharge.

In the European Union, regulation of the aquaculture sector is under the remit of the Common Fisheries Policy (CFP). In 2002 the European Commission addressed the sustainability of this industry. The Common Fisheries Policy, which covers European aquaculture developments, recognizes that the way forward to a sustainable industry is through an ecosystem based approach. Community regulations for fisheries and aquaculture specifically acknowledge that it is necessary to include rules for the monitoring of conservation and resource management, and that Member States shall adopt provisions to comply with the objectives of regular monitoring of activities and technical controls, particularly in development of the aquaculture industry in coastal areas. The submission of statistics on aquaculture products is also a requirement at a European level. This resulted from an acknowledgement of the impact of aquaculture on regional development and on the environment. EU Member States are required to ensure that all aquaculture enterprises operate within the rules on environmental protection. Most of the legislation takes the form of directives adopted by the EU which are translated into detailed national rules and procedures.

The WFD directive provides an approach for water management based on river basins, the natural geographical and hydrological units to protect aquatic ecosystems. The directive addresses inland surface waters, transitional waters, coastal waters and groundwater and has implications for fisheries and aquaculture activities. The WFD has been brought into force nationally in the EU through different Acts, and defined national competent authorities are responsible for implementing the WFD. The Directive prescribes the establishment of ecologically based environmental targets for watercourses and related fjords and coastal waters. In order to meet the environmental target for water that is satisfactory both ecologically and chemically, the countries involved are required to characterize their waterbodies and to establish monitoring strategies etc. Various countries have different time lines for implementation of the WFD, in the Kingdom of Norway the Directive shall be fully implemented by 2015. National regulations based on the WFD define the volume and type or water permitted to be extracted from groundwater and/or surface. These regulations also set water quality criteria for effluent discharge into receiving waters.

Current and future issues and bottlenecks

Many of the drivers for the growth of European aquaculture are found at regional or national levels however the European Commission plays a central role in the potential development of aquaculture in Europe. While there has been consistent growth in salmon culture in Northern Europe (primarily in the Kingdom of Norway), aquaculture production in Mid-Europe has remained fairly constant in the last decade. A major bottleneck for aquaculture in this region is the competition for resources in these countries which have high population densities compared to Northern Europe.

A risk assessment of the environmental effects of fish farming was recently conducted by the Institute of Marine Research, at the request of the Norwegian Ministry of Fisheries and Coastal Affairs (Aure *et al.*, 2010). The main risks to the environment were identified as the spread of salmon lice (*Lepeophtheirus salmonis*) and genetic effects of escaped farmed Atlantic salmon on wild fish. With regards to the discharge of nutrients (nitrogen and phosphorous) and organic matter from sea cages, monitoring of 300 fish farm locations indicated that only two had poor conditions with respect to organic loading and eutrophication according to the classification of the standard NS9410, MOM part B. Most of the phosphorous released from salmon cages is organically bound and sinks out of the euphotic zone. Inorganic phosphorous is seldom a limiting

factor for algal production along the Norwegian coastline. The MOM model was used to calculate the nitrogen and phosphorous release from salmon farms (sea cages). It was estimated that approximately 10.3 kg dissolved nitrogen and 1.7 kg dissolved phosphorous is released per tonne of salmon produced. Most salmonid farming in the Kingdom of Norway is from the coast of Rogaland and northwards and these areas are fairly oligotrophic, and have relatively strong currents and high levels of water exchange. The typical current speed along the coast is 20–50 cm s^{-1}, with a maximum of approximately 100 cm s^{-1}. Water transport in the top 30 metres of the coastal current is about 0.3 million m^3 in the South and increases to approximately 1 million m^3 in the North. Based on knowledge regarding water transport and typical nitrogen and phosphorous measurements along the coast it is estimated that the contribution of nutrients from fish farming to the background levels of nutrients ranges from 1–1.5 percent in the South to <0.1–0.4 percent in the North. This demonstrates that the release of nutrients from aquaculture has an insignificant effect on the nutrient levels in coastal waters (Aure *et al*., 2010). Measurements from areas with high densities of fish farms in Chile, Scotland, Mediterranean, and the Kingdom of Norway (Soto and Norambuena, 2004; Gowen and Ezzi, 1994; Pitta *et al*., 2006; and Husa *et al*., 2010) show that there is little risk of regional eutrophication of coastal waters in areas with good water exchange.

Several studies have shown that the effect of fish farming on benthic conditions is local, and is limited to a few hundred metres from the cages (Aure *et al*., 2010). The degree of influence both local and regional depends on whether the input from the fish farm is adapted to the carrying capacity at the site. At a regional level in the Kingdom of Norway it does not appear that the sea bed is overloaded with organic matter from aquaculture.

Recommendations

In order to expand aquaculture in European coastal waterbodies farming techniques should be developed to reduce environmental impact. In Norway this involves combating the problem of salmon lice and reducing the number of escapees from salmon farms. An increased production from inland waterbodies is most likely achievable by intensification at existing sites and further development of recirculation aquaculture systems to reduce water and energy consumption and to reduce nutrient emission to the environment.

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Aquaculture site selection and carrying capacity estimates for inland and coastal aquaculture in the Arab Republic of Egypt

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Abstract

This paper reviews Egyptian aquaculture development and how carrying capacity management status can assist and protect the durability of this important industry. Rapid expansion of the Egyptian coastal aquaculture is identified as the major problem affecting the sustainable development of aquaculture, resulting in several important issues such as environmental pressure and pollution caused by agricultural and industrial development and the continuous increase of fertilization and fed fish in the north Nile delta zone. There are several laws and regulations dealing with the Egyptian fisheries, aquaculture sectors, but still lack of effective monitoring and legislation on the aquaculture site. The Nile Delta is the only delta in the Arab Republic of Egypt with a 230 km long, 360 km wide and triangular in shape. The Nile Valley and the Delta occupy about 33 000 km^2, which account for less than 4 percent of the total area. Egyptian fish farms produced over 705 490 tonnes of finfish in 2009, or about 65 percent of the country's total freshwater and marine fish production, providing a cheap source of protein for the country's 75.2 million people in 2008. In the last 10 years the aquaculture activity has been tremendously increased 3.3 times, where in 1999 aquaculture production was 214 thousand tonnes and becomes around 706 thousand tonnes in 2009. This paper provides some relevant recommendations on the effluent discharge of fish farms, as no concrete zoning scheme of land and water areas suitable for aquaculture is taking into the requirements, which can create problems on the water quality, environment and can influence on the community welfare. It is clear that the current bottlenecks limiting the reasonable aquaculture site selection and carrying capacity management. Different strategy proposals will be discussed to maintain a sustainable Egyptian aquaculture, from any retardation.

Introduction

The Arab Republic of Egypt is located in the North-Eastern and South-Western corners of Africa and Asia respectively. The Nile Delta is the only delta in the Arab

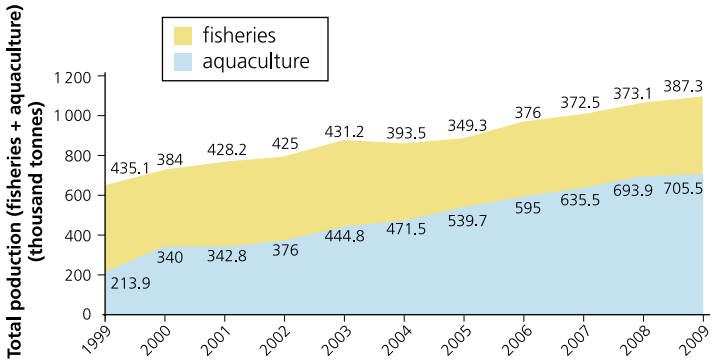
Republic of Egypt with a 230 km long, 360 km wide and triangular in shape. The Nile Valley and the Delta occupy about 33 000 km^2, which account for less than 4 percent of the total area. The Arab Republic of Egypt is covered almost entirely by desert, 99 percent of the Arab Republic of Egypt's population living in just 5 percent of its land area, mainly concentrated along the Nile valley and the river's northern delta, which splinters out into the Mediterranean.

According to the General Authority for Fish Resources Development (GAFRD) statistics (GAFRD, 2010) and (Capmas, 2010a and b) the total fish production in the Arab Republic of Egypt was 1 092 888 tonnes where 705 490 tonnes were produced through aquaculture. The Arab Republic of Egypt has built the largest aquaculture industry in Africa, accounting for four out of every five fish farmed on the continent. Egyptian fish farms produced over 705 490 tonnes of finfish in 2009, or about 65 percent of the country's total freshwater and marine fish production, providing a cheap source of protein for the country's 75.2 million people in 2008. In the last 10 years the aquaculture activity has been tremendously increased 3.3 times, where in 1999 aquaculture production was 214 thousand tonnes and becomes around 706 thousand tonnes in 2009 (Figure 1).

GAFRD plans to develop the country's aquaculture industry further, and has set a goal of 1.2 million tonnes of farmed fish, or about 75 percent of total fish production, by 2017. Its two-pronged strategy aims to increase the productivity of aquaculture operations using underground water, while encouraging investment in mariculture (Prof. Dr. Mohamed Fathy Osman, GAFRD's chairman – personal communication).

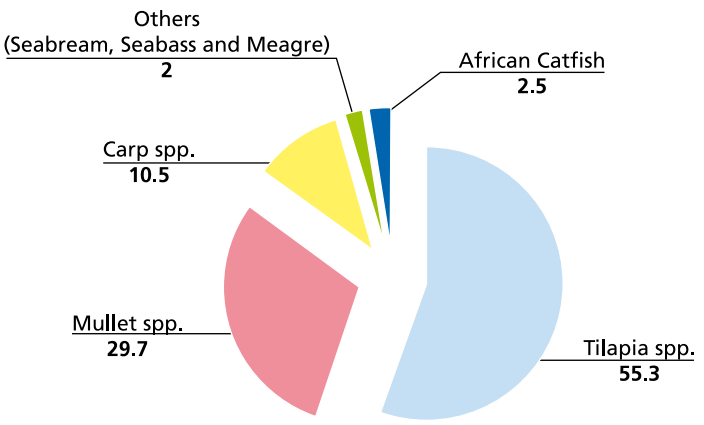
Three decades ago tilapia and mullet were the main species reared in extensive earthen ponds. Today ten finfish (Tilapia, Mullet *spp*.; Grass Carp, Silver Carp; African Catfish; Bayad; Gilthead seabream; European sea bass; Meagre and Solia besides four crustacean species; *Macrobrachium rosenbergii*, *Penaeus semisulcatus*; *P. japonicus* and *P. indicus*), are playing an important role in the aquaculture production. During 2009 tilapia has chaired 55.3 percent of the total aquaculture production, followed by Mullet *spp*., Carp *spp*., African catfish and other species (Gilthead seabream, European seabass,etc.), 29.7 percent, 10.5 percent, 2.5 percent and 2 percent respectively (Figure 2).

FIGURE 1
Fisheries and aquaculture production in Egypt for the period 1999-2009



Source: GAFRD (2010).

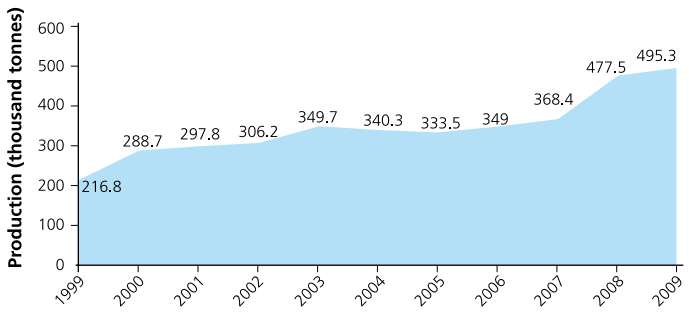
FIGURE 2
Egyptian aquaculture production ranking percent per fish species in 2009



Source: GAFRD (2010).

During the period from the period from 1999 to 2009 the tilapia total production in the Arab Republic of Egypt has increased 2.3 times, where in 1999 tilapia culture was 216.8 thousand tonnes and becomes around 495.3 thousand tonnes in 2009 (Figure 3), due to a shift to intensive rearing methods and to faster growing species such as mono-sex tilapia (GAFRD, 2010).

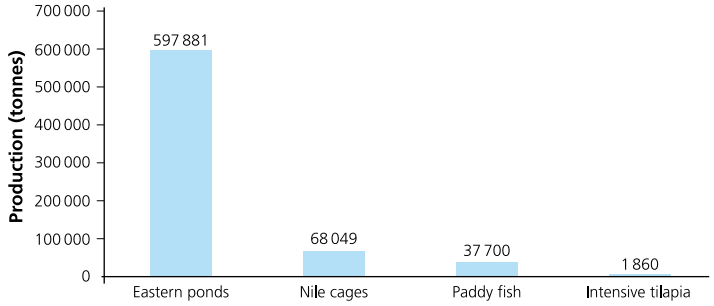
FIGURE 3
Total Tilapia production in Egypt for the period 1999-2009



Source: GAFRD (2010).

From the actual major culture system, earthen ponds production rank in the first with 84.8 percent of the total Egyptian aquaculture production, while cage culture follow by 9.7 percent, paddy filed come next with 5.3 percent of the total and at lastly 0.2 percent for tilapia intensive culture production in cement tanks mostly in the desert and arid zones and integrated with agriculture activities (Figure 4).

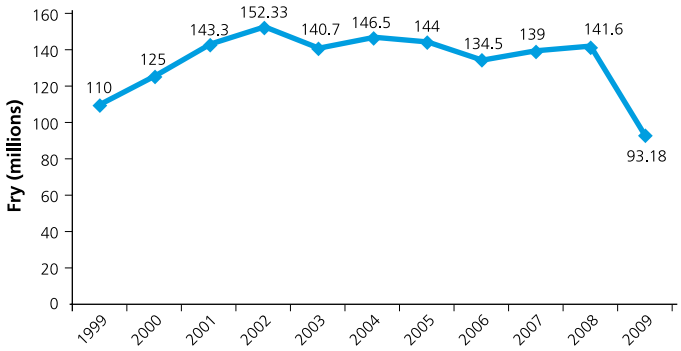
FIGURE 4
Egyptian aquaculture production system types in 2009



Source: GAFRD (2010).

Extensive and semi intensive earthen ponds for a total surface of around 151 818 hectares practiced in the Arab Republic of Egypt are characterized by medium stocking densities and limited water exchange rate. The public sector is charring only for less than 5 percent of the total surface and > 95 percent for the private sectors. The private sector is producing > 99.0 percent of the total aquaculture production, and the public sector contributes only with < 1.0 percent. The public sector is contributing more with the fry and fingerlings, extension support, artificial feeds and research support. The number of finfish fry currently produced from 113 authorized hatcheries has increased several folds compared to a few years ago, to reach 305 million seeds in year 2009. Figure (5) reports the tilapia fry production from authorized hatcheries for the period 1999–2009 (GAFRD, 2010). In addition more than 500 Nile tilapia not authorized hatcheries are charring with fry production for an estimated production of more than one billion fry. The public sector is charring for 71 percent of the total seed production and 29 percent for the private sectors. From the total fry produced 92 percent

FIGURE 5
Tilapia fry production from authorized hatcheries for the period 1999-2009



Source: GAFRD (2010).

are fresh water species mainly Nile tilapia; common carp; grass carp and silver carp. The 8 percent remain are marine aquatic finfish and crustacean species mainly Gilthead seabream; European sea bass; Solia and Green tiger shrimp.

Wild finfish fry, mainly mullet species, are collected from the wild, during the last 10 years (2000–2009), the maximum yield has reached 137.0 million in 2002 and the minimum capture was 41.0 million in 2006. In year 2009 the wild mullet fry cached was estimated to 57.4 million.

Water available for the Egyptian aquaculture industry

The Arab Republic of Egypt's main source of freshwater is the Nile River. The river supplies 56.8 billion m^3 of freshwater every year, which represents 97 percent of all renewable water resources in the Arab Republic of Egypt. Average rainfall in the Arab Republic of Egypt is estimated at 18 mm or 1.8 billion m^3 per year. Furthermore, the Arab Republic of Egypt has four different groundwater aquifers: the Nile Aquifer, the Nubian Sandstone Aquifer, the Moghra Aquifer and the Coastal Aquifer. The population has doubled in the last 40 years from 37 million in 1970 to 72 million in 2005 and is expected to reach 95 million in 2025, thus increasing the related water demands for public water supply and economic activities, in particular agriculture. The annual population growth rate decreased from 2.8 percent in the period 1976–86 to 2.1 percent in the period 1986–96, and has decreased further to 1.9 percent according to the 2004 estimate. These figures give an impression that the Arab Republic of Egypt is a water rich country but the growth in population makes it a water scarce country. Since 2005, the Arab Republic of Egypt is classified as a water scarce country as it has less than 1000 m^3 of fresh water per year and capita. Furthermore, it is forecasted that in 2025 the population will reach 95 million, which would mean a per capita share of only 600 m^3 per year. The prime water consumer in the Arab Republic of Egypt is the agricultural sector, with its share exceeding 82 percent of the total gross demand for water. Municipal and industrial uses account for 15 percent of the total water consumption in the country, while navigation and hydropower generation are considered as non-consumptive uses. Industry and mining account for nearly 18 percent of the GDP and almost 14 percent of total employment (Abdel-Gawad, Kandil and Sadek, 2004; Abdel-Gawad, 2008).

In the Arab Republic of Egypt the water resources both fresh and brackish water are the major constraints on further development, with use for potable water and land crop production having priority over aquaculture activities. The Arab Republic of Egypt has a rapidly expanding population and the government is concerned with future food security. The Nile is the nation's only renewable source of fresh water and this forms a bottle neck that sets limits to agriculture and its future expansion. Making use of this limited resource in the most efficient way is of great importance for the Arab Republic of Egypt (and for other countries with limited fresh water supplies).

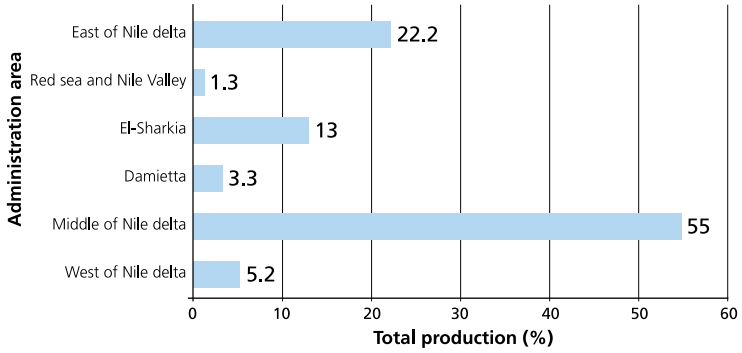
According to GAFRD's law No 124/1983 (GAAAP, 1993) only brackish and marine water, and infertile land that is not suitable for agriculture, can be used in aquaculture. Water supply should be restricted to water from lakes and agriculture drains. The use of fresh (i.e. irrigation) water is prohibited, although hatcheries established by the government are exempted from this rule. The use for potable water and land crop production has priority over aquaculture activities in the Arab Republic of Egypt. A key policy issue in the Arab Republic of Egypt is planning to increase the reused agriculture drainage water for the delta region in year 2014 to reach 1.4 times the actual quantity reuse in 2002 3 219 million m^3/year. In three Nile delta regions, the Integrated Irrigation Improvement and Management Project (IIIMP) is actually implementing an irrigation system improvement almost 235 thousand ha would be the focus for irrigation improvement of agriculture land in

four different governorates. It is perceived that drainage water quantity and salinity would negatively be impacted (-12 percent and 4 percent, respectively). Different environmental impacts will effect on the aquaculture ecosystem production in the Nile delta regions as water available for fish earthen ponds will be not adequate and the increase of salinity could effect on both production capacity and production composition. In addition, paddy field and spreading grass carps in drainage water channels could be negatively affected. This policy could retard the development of the aquaculture. The new policy of irrigation strategy could affect 60 percent of the actual aquaculture production (Anonymous, 2004).

Actual and future projection of the Egyptian aquaculture sites:

In the Arab Republic of Egypt, the most important inland aquaculture sites are primitive mouth of the Nile branch, paddy field, hosha, reservoirs in northern coastal lakes, inland lakes; land based earthen ponds, and cement and/or lining intensive tanks. From the actual major culture system, the extensive and semi-intensive sectors are paddy field ranks first with 575 210 ha (79.0 percent of the total Egyptian aquaculture land based), while brackish and marine water earthen ponds surface follow with 151 818 ha (21.0 percent). For the intensive culture the Nile cages in the mouth of Rashid branch ranks first with 5.2 million m^3 (95.0 percent of the total Egyptian intensive aquaculture), while cement and/or lining tanks in the desert follow with 300 400 m^3 (5.0 percent). From the actual major culture system, the extensive and semi-intensive sectors are paddy field ranks first with 575 210 ha (79.0 percent of the total Egyptian aquaculture land based), while brackish and marine water earthen ponds surface follow with 151 818 ha (21.0 percent).The Egyptian aquaculture map showed that fish farming activities are more concentrated in sub-regions of the Nile delta, where the water resources are available and non-agricultural lands. Other very few projects are located in Upper Egypt region, the Mediterranean Sea coast and the Red Sea coasts. GAFRD (2010) has estimated the total number of private brackish and marine earthen ponds farms in 2010, for 7 759 fish farms (69.0 percent under the leased license contract with GAFRD and 31.0 percent under the owned license in depended contract) distributed on 76 818 ha of land. The earthen ponds geographical distribution are mainly concentrated in the Nile delta, ranks first with 68.9 percent in the middle of delta, follow with 13.0 percent in north east of delta specially in Damietta governorate, contribute after that the west of delta with 11.6 percent. The remain of the earthen ponds area are located in the east of delta, associated with the Nile valley and red sea for only 6.5 percent (Figure 6). Other 75 thousands ha of earthen ponds are contracted for a short fish farm temporary contract period, for the need of cleaning the land from salt till they can shift to the plant production again.

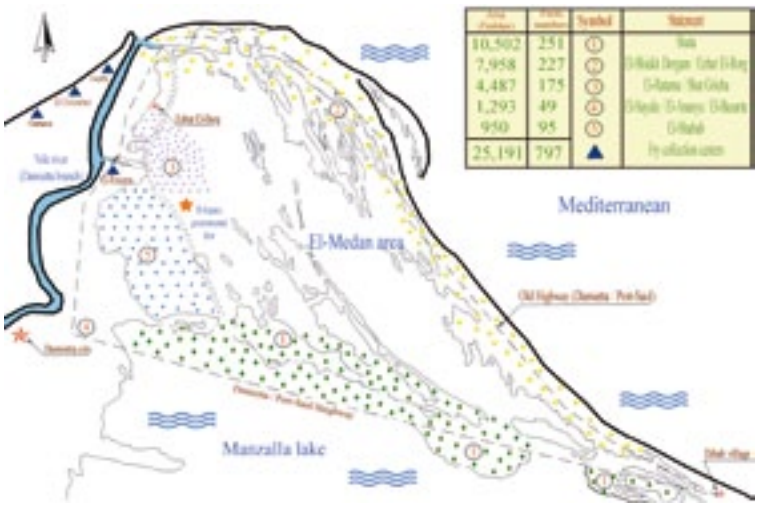
FIGURE 6
Geographical distribution of Egyptian private fish earthen ponds production in 2009



Source: GAFRD (2010).

Sadek (2010a) has clarified two opposite examples of the waterbody change in Nile delta. The waterbody in lake Manzala has changed during 1973–2003, from 1 250 km^2 in 1973 to 850 km^2 in 2003, due for drying shallow the lake boarder for the need of reclamation lands. Ended the decrease of the waterbody lake has created a pressure

FIGURE 7
Distribution of aquaculture in Dibah Triangle Zone. Damietta – Port-Said, Egypt



Source: Aquaculture Consultant Office (ACO), Designer: Mahmoud Asfoor.

FIGURE 8
Distribution of different water resources in Dibah Triangle Zone. Damietta – Port-Said, Egypt

Source: Aquaculture Consultant Office (ACO), Designer: Mahmoud Asfoor.

environment on the fisheries of the lake. The second opposite example is located in the Dibah Triangle Zone – DTZ (Figure 7) in Damietta and Port-Said Governorates. DTZ is part of a wider ecosystem that includes the Manzalah lake and riparian areas of the whole Nile delta. The water area includes a long sand beach with exchanges with the Mediterranean Sea, Manzala lake and freshwater from the Nile (Damietta branch), with many fish and shrimp ponds (Figure 8). It has already been an important aquaculture production fish area (especially Sea bream; Sea bass; Mullet and Meagre) and in addition marine shrimps (*Penaeus semisulcatus*). The total surface of the DTZ is around 23 110 hectares, from which 46 percent for aquaculture and 54 percent for open fisheries. The TDA's waterbody complex has increased from 161 km^2 in 1987 to 168 km^2 in 2000, due the increase of mariculture farms. Ended this industry has increased an unstable environment for the area.

5. Environmental carrying capacity status and issues

5.1 Freshwater aquaculture

Rice-fish culture

The Arab Republic of Egypt is the largest rice producer in the Middle East and African countries. Egyptian rice yield is one of the highest in the world (9.1 tonne per ha. There is now considerable potential for rice-fish farming to further expand its contribution to improve the livelihoods and food security of the rural families (Suloma and Ogatai, 2006).

Field experiments of rice-fish culture using common carp in the early 1970s led to encouraging results. The rice-fish culture has contributed to the increase of total aquaculture production in the Arab Republic of Egypt. The improved rice-fish culture can effectively give a great contribution in a short time (Essawi and Ishak, 1975). In 2009, rice-fish culture was practiced in 575 210 ha and contributed for 37 700 tonnes about 5.5 percent of the total aquaculture production in the country, from which 44 percent tilapia; 31 percent common carp and 25 percent African catfish.

The stocking and growing of fish in an Egyptian rice field is basically an extensive aquaculture system that mainly relies on the natural food in the field. One constraint of the concurrent system is that the growing period of the fish is limited to that of rice, which is usually 100 to 150 days. The rice-fish project under the supervision of GAFRD is distributing free of charge the common seed carp fry to the farmers. The average production per ha was 50.0 kg for farmers within the rice-fish project, which 28 percent of the total area of rice-fish in the Arab Republic of Egypt, and decreasing to 19.0 kg/ha for the other farmers using agriculture land out side the project (GAFRD, 2010).

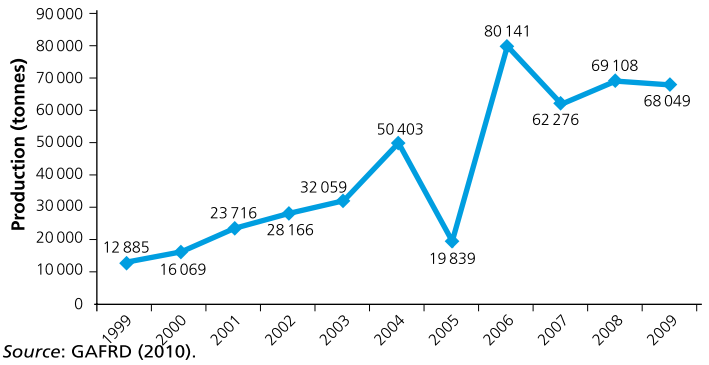
Nile cages

In the 1985 the first eight tilapia cages were established in Damietta Nile branch with a yearly production 1.92 tonnes, since this date there was a rapid increase in the cage numbers and cage production, reaching 24 718 cages and 68 049 tonnes (86 percent Silver carp and 14 percent tilapia) respectively in 2009 (Figure 9).

The environmental conditions in the Nile is no longer suitable for aquaculture, as the water environment in the areas were polluted in varying degrees by inorganic nitrogen, organic substances, phosphorus, and heavy metals. Sadek, Osman and Mezayen (2006) have reported that in the Arab Republic of Egypt the water resources both fresh and brackish water are the major constraints on further development, with use for potable water and land crop production having priority over aquaculture activities. Because of the legislation and environmental pressures of the cages, plus a conflict with other activities, the Egyptian authorities have removed all the Nile cages behind the two final fresh water control dams in the two Nile branches (Edfina and Faraskour).

Today most of the tilapia cage projects were located in two governorates Kafr-El-Sheik and Beheira near Rashid branch at the end of the Nile mouth with slightly brackish water. Few tilapia cages are located in El-Rayan inland lake in the governorate of Fayum.

FIGURE 9
Nile cages production in Egypt for the period 1999–2009



Source: GAFRD (2010).

5.2 Earthen ponds

Extensive

A famous regime for aquaculture called HOSHA system was commonly practiced during forties to seventies. The farmer build his muddy pond on the lake shore, allow water from the lake to come in, with no control for species or size of the fish, providing any agriculture products as food, maybe some organic fertilizers for 2–3 months duration, then pump the water out of the pond and harvest everything. In the extensive culture natural food, produced through pond fertilization, is considered an important element of fish growth during early growth stages. At later fattening stages supplemental feeds were applied. Sadek (2010a) has figured that the yearly production per hectare will fluctuate in the extensive culture ponds (polyculture Nile tilapia, carp *spp*. and mullet *spp*.) and/or (seabream, seabass and mullet *spp*.) from 500 kg to 1 tonne/ha. The extensive system is more popular, where, farmers stock ponds at low densities, and fish derive most of their nutrition from the natural food present in ponds. Also

fish farmers feed sea bream with wild collected fish (*Tilapia zillii*) and small size shrimp (*Palaemon spp*.) caught from northern delta lakes.

Semi-intensive

Modern aquaculture activities started at late seventies when the government established two big pilot projects in Kafer-El-Sheikh governorate seed production at Foua and the other for market size 500 h, fish farm at Zawia, at the same time, training for technicians had also been provided by the government in more advanced countries in aquaculture. During this time growing fish for market size was relatively successful. Production of mullet reached 1 tonne/ha using seed from wild catch and wheat meddling or rice brine as food.

Radwan (2008) has focused on the development of tilapia farming in a relatively short period (1990–2008) in the Nile delta with is low land, especially Kafr-El-Sheik governorate (Burullus Lake and surrounding area), which is today is a major economic aquaculture activity with more than 61 thousands hectares. GAFRD (2010) has reviewed that in 1990 tilapia aquaculture production was estimated to 20 thousand tonnes and reached 390.3 thousands in 2009 tonnes, which represent 55 percent of the total aquaculture production. The most important factors that resulted in such booming in production business described are:

The Arab Republic of Egypt is a Mediterranean country characterized by cold winter as the air temperature could reach 5 degree Celsius or less at winter and water temperature could reach at that time 10 degree Celsius or less. Winter in the Arab Republic of Egypt is not suitable for Nile tilapia, in the nature this fish migrate to the south seeking warmer water in this winter time. This weather in the Arab Republic of Egypt limits the growth of Nile tilapia until the year 1991 when the commercial production of mono sex tilapia under green house in ponds proved it was an efficient and profitable technique (Radwan, 2008).

The yearly production per hectare will fluctuate in the semi-intensive culture earthen ponds from 4.5 to 20 tonnes/ha in monoculture system (tilapia or Meagre) and polyculture system (Nile tilapia associated with mullet *spp*.). During the last ten years, applied semi-intensive cultures indicates that fish farmers can grow more Nile tilapia or meagre and earn higher profits by using improved production methods (Sadek, 2010a).

Sadek (2010b) has reviewed the shrimp aquaculture development and describes the lessons learned to date in the Arab Republic of Egypt, as well as the problems and prospects for future development. During the last three decades, there has been increasing investment in shrimp farming in the Arab Republic of Egypt and there are clear indications for further investments, but still the production results are not commercially positive. The Arab Republic of Egypt is just beginning to develop its potential, and the government is encouraging shrimp farming. Three crustacean species are in the production *Penaeus semisulcatus*, *P. japonicus* and *P. indicus*. Today the Arab Republic of Egypt has two marine private hatcheries operate with a yearly production capacity of 400 million PL/year, and several farms in production with a total surface of around 1 000 ha. In addition two university research bodies operate marine finfish and shrimp hatcheries for research and training purposes at Alexandria and El-Arish. By the end of year 2009, the estimated annual heads-on production would have achieved 500 metric tonnes, which will represent only less than 2 percent of the Egyptian shrimp fisheries (Figure 10).

Shrimp farming in the Arab Republic of Egypt is characterized by extensive culture in Qarun inland lake and semi-intensive production systems using fertilizer and commercial feed. Most shrimp aquaculture is undertaken northeast and northwest of Nile delta near the Mediterranean Sea as well as along the Red Sea coast. Records of the production characteristics data for 24 artesian and commercial shrimp farms on different water salinity and soil types revealed difference in growth, survival and yields during the period 1993–2010. The management and production of these shrimp farms

FIGURE 10
Mariculture activities in Egypt

Source: Aquaculture Consultant Office (ACO), Designer: Mahmoud Asfoor.

during 90–150 days of grow-out are ranging for stocking densities (5 to 20 post larvae (PL)/m^2), survival rates (< 5 to 82 percent); average animal weight at final harvest (<10 to 32 gm) and shrimp yields average 26 to 864 kg/ha per year.

5.3 Egyptian desert intensive aquaculture

El-Guindy (2006), Sadek (2011) and Sadek *et al.* (2011) have reported that today the actual Egyptian commercial aquaculture desert farms are 20, with a total surface around 893 hectares and total yearly production around 13 000 tonnes, located in seven different provinces. These commercial farms are capable to produce (from < 5 to 6000 tonnes/year) different finfish species (Nile tilapia (*Oreochromis niloticus)*; Red tilapia; North African catfish *(Clarias gariepinus)*; Common Carp *(Cyprinus carpio);* Silver Carp *(Hypophthalmichthys molitrix);* Grass Carp *(Ctenopharyngodon idellus);* European seabass *(Dicentrarchus labrax);* Gilthead seabream *(Sparus aurata)* and exotic species mainly Koi; Fantail; Molly). The water source is the underground water and agricultural drainage water with different salinity ranging from < 0.5 to 26 gr/L and with an ambient water temperature ranging from 22 to 26 °C. Most of the commercial farms are using flow through system associated to the agriculture irrigation land, to give an opportunity to produce three different crops (fish/plant/sheep). Only two commercial farms are using both flow through and recycle systems, remain farms are using only flow through system integrated to the agriculture lands.

The tilapia (*Oreochromis niloticus* and *O. aureus*, or sex-reversed red tilapias) is one of the most promising species, among other edible and ornamental fish species. Due to suitable warm climate and plenty of warm constant underground water, the tilapia are continuously grown, round-year, to marketable size of 250–400 grams in 6–8 months, in biomass extending the densities of 20–30 kg/m^3.

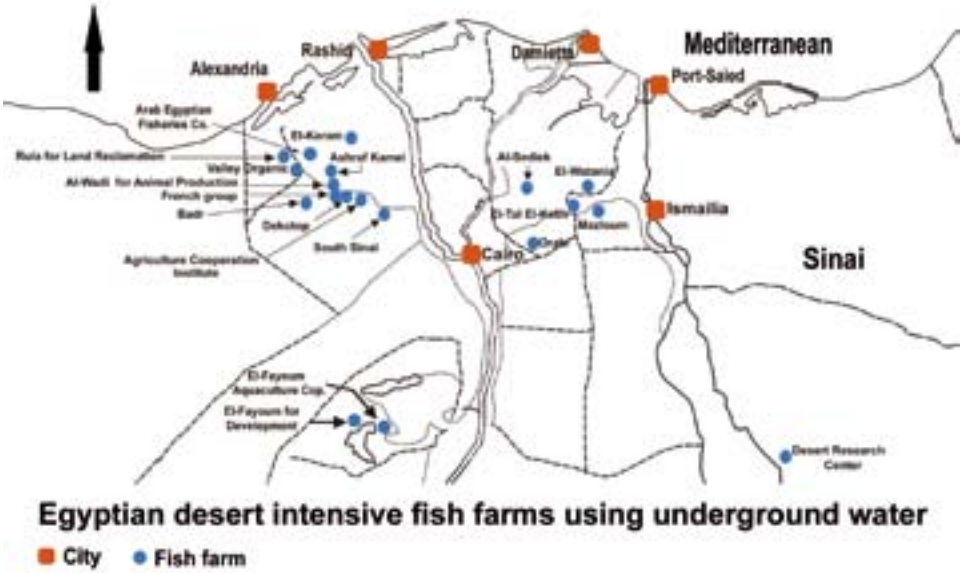
Although the water contains variable high brackish salt concentrations (> 25 gr/L), was utilized for integrated agriculture, e.g. irrigation of Salicornia crops combined

with intensive European seabass and Gilthead seabream aquaculture, with a yearly production 100 tonnes/year of both species.

Most of the commercial farms are purchasing their fish fry from the local market, and only five of these farms have their own hatchery. Different issues are effecting the developing of these commercial aquatic desert farms, mainly the water quantity/ quality; excess of effluent water; fingerlings supply; feed quality; feed prices; over head of the production cost; need for technical experiences; marine fish diseases and availability of credit

Egyptian desert aquaculture could be a durable industry as even lower economic returns of conventional crops are acceptable in locations where no other opportunities exist for agricultural production. Facilitate aquaculture development by actively extending the FFF's messages: Fish does not consume, but only uses water; Fish farming is a clean production system and fish farming discharge water has added value for agriculture (Figure 11).

FIGURE 11
Egyptian desert intensive fish farms using underground water



Source: Aquaculture Consultant Office (ACO), Designer: Mahmoud Asfoor.

5. Economic analysis of fish farming

El-Naggar, Nasr-Alla and Kareem (2008) have examined factors influencing the fish farming enterprise in Behera with a view to finding out what are the socio-economic characteristics of the farmers, identify, and determine various performance indicators of economic viability or profitability, correlation between the production variables and the total revenue, factors influencing profitability, and identifying problems militating against 15 fish farmers in the Nile delta.

The data collected included: socio-economic characteristics (age, gender, marital status, educational level etc), production costs; cost of feed, cost of fish seed, other costs (maintenance, fertilizer, fuel, transport etc) and output data per the period under review.

Sadek, Sabry and Asfoor (2009) and Sadek (2010a) have examined the economic analysis of Egyptian fish farming in different Nile Delta areas: area A (Kafr El-Sheik) and area B1 and B2 (Damietta). Sample survey of 215 farmers representing the fish farming community in areas was used. The study was conducted from April 2006 to October 2008 covering one production season of 8 months for tilapia monoculture; 15 months for meagre monoculture and 24 months for seabream/seabass/mullet polyculture.

Different performance indicators of the selected Egyptian earthen fish farms management characteristics were considered (land ownership; age of respondents; farm Size-ha; job status; marital status; farm managers skill; fish stocking fry/ha in both monoculture and polyculture; fertilization; feed/feeding; fish yield Kg/ha; and source of finance).

In area (A) tilapia monoculture was dominated. The study result revealed that the average age of fish operators was (45 years), majority are married (71.5 percent), fairly level of education (67 percent) and majority with rented land ownership (69.9 percent) and tilapia represented over 91 percent of total fish harvested. The top ranking serious constraints facing fish farmers in that area were found high prices of fish feed; declining fish prices and lack of credit finance. Feed costs per kg of fish were LE 3.10, representing 63.3 percent of the production costs. The break-even analysis showed average production costs of LE 6.80/kg of fish while the sales price is LE 7.25/kg. Result figures showed that there is high positive relationship between cost of feed and extra labors to the level of farm income.

The study results in area (B-1) revealed that the meagre monoculture was applied. The performance indicator showed that the average age of fish operators was (49.5 years), majority are married (80.5 percent), highly level of education (59 percent) and majority with rented land ownership (77.3 percent). Two main serious constraints were found high prices of fish seed, availability of trash fish feed, low water quality source and lack of experience of fish diseases. The break-even analysis showed average production costs of LE 15.0/kg of fish while the sales price is LE 25.0/kg. Result figures showed that there is high positive relationship between high fish density, availability of trash fish feed and water exchange rate to the level of farm income

In area (B-2) the polyculture of seabream/seabass/mullet was widespread. The performance indicator showed that the average age of fish operators was (52.0 years), majority are married (86.3 percent), medium level of education (41 percent) and majority with rented land ownership (89.0 percent). Several serious constraints were found high prices and low quality of fish seed; availability of good and acceptable price of marine fish feed and poor to medium water quality source. The break-even analysis figured average production costs of LE 30.0, 35 and 8/kg of seabream; seabass and mullet respectively, while the sales price is LE 47.0, 58 and 16/kg respectively. Result figures showed that there is high positive relationship between increasing the water exchange rate, high fish density using fingerlings and not fry, availability of good and acceptable of marine fish feed to the level of farm income.

6. Aquaculture constraints

Egyptian aquaculture has a largest industry and most of the production comes from thousands of small-scale farms owned by individual farmers, which brings the difficulty in coordinating farm scales and distribution for the local fisheries administrative authorities. During the last three decades it was appear a development change of the Egyptian aquaculture structure. The ecosystem impacts of species and farming practices on ecosystem balance, water quality and environmental health.

Environmental Impacts of Aquaculture on the fisheries of the Egyptian northern costal lakes, due for the nutrient discharge and accumulation of waste in north Nile Delta:

- uneaten fish food, fish excretory products and organic matter (components of solid and dissolved waste are various forms of carbon, nitrogen and phosphorous);
- can alter the species composition and density of phytoplankton;
- increasing the risk of toxic algal blooms; and
- effects on the substrate ecosystem = accumulation of organic matter on the lake/seabed = can produce major changes in the sediment chemistry.

Although some internationally growing intensive farming technique such as tilapia cage farming and tilapia hatchery also have deficiencies, e.g. genetic pollution caused by fish escape, disease transmission, etc., and some may have caused serious environmental problems in somewhere, but could be evitable if all the needed measures are complete.

Tilapia hatcheries have deficiencies, e.g. genetic pollution caused by fish escape, disease transmission, and some may have caused serious environmental problems in somewhere, but could be evitable if all the needed measures are complete.

As the result of the increase in the tilapia production from 20 thousands in 1990 until it reached 390.3 thousand tonnes by 2009, tilapia price started to decline since 1998 to reach level of brake even at 2002. Because of the dramatic increase of the food cost, many producers witnessed great loss during the last few years some of them are already out of business while others are struggling hopping to balance between the cost and the selling price, moreover the economic effect of business in the golden period 1991 – 2000 is still in the background of the decision-makers which creates another financial load on the producer due to un realistic taxes. A drop in the production is expected and there is an urgent need for solving the export problems and to have an added – value technology in the Arab Republic of Egypt. The boom of production consequently accompanied by selling price decline to reach cost even by 2002 without any considerable increase while production coast increased 300 percent, however developing the production technology to be more efficient technically and economically is a major concern of Kafr-El-Sheikh aquaculture.

Sadek (2010a) has reported the changes in the prices of main raw materials used in fish feed industry during the period 1992–2009. During the same period, the price of tilapia feed (25 percent protein) has increased from US$165/ tonne in 1995 to US$217/tonne and in 2009 (US$550/tonne in 2009). The Arab Republic of Egypt has more than 20 facilities of aquatic feed (5 of them are extruder) capable to produce around 500 thousand tonnes/year. The development of the Egyptian aquaculture will need more importation of fish feed ingredients, but this will demand increase the supply of foreign currency.

Recommendations:

- Estimating the carrying capacity and production capacity culturing different aquatic ecosystems (rice field; Nile cages; brackish water earthen ponds and intensive desert aquaculture), with different aquatic finfish, fresh-water prawn and marine shrimp. The evaluation balance of the primary nutrients involved in the different aquaculture ecosystem activities, could be realized by estimating the environmental carrying capacity of areas and nutrients for maximizing the output performance;
- Evaluating the expected future water budget available for aquaculture, due to the future limitation of fresh and brackish water;
- Considering the assigned aquaculture zone and individual farm site selection, with development of current legislation, regulations and actual compliance;
- Adopting an effective program of fish farming among small-scale farmers:
  - comparing the actual stocking rate for the extensive culture (<1–2 fish/m^3) using different weight of wild fish or fish produced from hatchery (2 to 20 gm/fish) without aeration and with higher stocking associated with aeration;
  - applying different water exchange practices;
  - constructing different size of earthen ponds with different water depth, comparing the actual popular dimension (0.5 to 1 ha with 2 meter water depth) with larger earthen ponds;
  - comparing using trash fish/shrimp; artificial compressed pellet or extruded feed;
  - studying the economic aspects of small; medium and large fish farms.
  - evaluating the local and export marketing of fish to bring the maximum benefit to the farmers; and
  - supporting applied research on the different aspects of fish with governmental and private NG bodies.
- Covering gaps in information and data on carrying capacity and site selection issues;

- Improving and applying the ecosystem approach to aquaculture (EAA) for the actual and new aquaculture projects, in the different aquaculture geographical area effluent discharge and if fish farms should be equipped with effluent treatment facility;
- Mitigating shrimp farming technical and institutional constrains mainly (quality of seed production and their limited seasonality from April to August; competition and restrictions on coastal land; availability of specialized feeds; shortage of technical manpower; lack of information on the environmental impact and impact of disease stress). Shrimp culture can develop rapidly in the coming decade if the government and NGO bodies could Overall shrimp sustainable development production efficiency will be facilitated by evaluating the production parameters of the different shrimp species in the two different ecosystems in the Red Sea and the Mediterranean Sea coasts; decreasing the cost of PL and juvenile around the year; enhancing the availability of skilled capacity staff; achieving in applied scientific research; enhancing high quality formulated feed and understanding of shrimp pathogens and microbial ecology, by the use of environmentally friendly aquatic drugs);
- Estimating the water needs and salinity tolerance of common Egyptian crops (fish/crustacean/cloves/animal production) in the desert aquaculture to reach a durable development industry, with the encouraging using the RAS in the desert aquaculture feasible projects. In addition research effort would be needed to identify non-conventional crops using brackish aquifers in the application of *Salicornia* irrigation systems and animal production. Crops are adapted to brackish irrigation the economic returns are always rather low, even when more salt-resistant varieties are used;
- Evaluating the specific and applied research projects to the carrying capacity. Effort would be needed to establish pilot projects for the different Egyptian aquaculture ecosystems including: rice field; Nile cages; brackish/marine water earthen ponds and intensive desert aquaculture with an emphasis to the aquaponic opportunities;
- Supporting artesian and commercial financial credit for aquaculture projects, which could open new prospects for an EAA development taking into consideration the carrying capacity of the different geographical aquatic ecosystem; and
- Assisting the existing ten Egyptian aquaculture producer's associations and societies for assisting artesian fish farmers and commercial farms to pioneer the management culture techniques; increase the availability of commercial inputs, improved marketing distribution channels and facilitate credit.

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Aquaculture site selection and carrying capacity estimates for inland and coastal aquaculture in West Africa

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Abstract

This article reviews aquaculture site selection and carrying capacity estimates for the West African region. Site selection within the sub-region varied was based on the type of production system employed. For water-based culture systems main considerations included physico-chemical properties of the waterbody, weather, shelter and depth. Considerations for land based systems included topography, soil type, availability of water and water quality. Legal issues, access, land-based facilities, security, economic and social considerations cut across both land and water based system

To ensure sustainable development of aquaculture, each of the countries had instituted some form of national legislation relating to environmental assessment and, which were undertaken following Environmental Impact Assessment (EIA) procedures. For some of the countries, however, these legislations applied to only large commercial farms.

Site assessment were undertaken using the traditional methods of resolving aquaculture site selection which are length, intensive and subjective, and cannot be efficient if site selection is to be based on the Ecological Approach to Aquaculture.

Introduction

In view of virtual stagnation in capture fish production, and as nations strive to meet the Millennium Development Goal of reducing poverty and hunger by half by 2015 (www.unicef.org/mdg/poverty.html), the importance of aquaculture to food security, income generation and indirect benefits of employment cannot be over emphasized, particularly when the role of aquaculture as a food producing sector is considered in combination with the importance of fish in the diets of many of the worlds' poorest nations. The aquaculture sector thus continues to grow worldwide at an average compounded rate of 8.1 percent per year (Lazard *et al.,* 2010), making it the fastest food growing sector.

Aquaculture growth involves the expansion of cultivated areas, higher density of aquaculture installations and increased use of feeds and other inputs. Being a resource-

based activity, which competes for economic, social, physical and ecological resources with other industries, its development could have negative impacts on other industries such as fisheries, agriculture, and tourism with environmental impacts, which can have social and economic implications (FAO, 2008). Site selection and carrying capacity estimates are believed to play key roles in the success of such projects.

Presented in the report is a review of aquaculture site selection and carrying capacity estimates in West Africa and it forms part of a global review of the subject. It provides a brief description of the West African region, the state of aquaculture development in the region and current criteria and approaches for site selection within the region considering current legislation, regulations and actual compliance, main carrying capacity and site selection issues, gaps in information and local needs. As well as key elements to be included (or improved) to bring existing site selection requirements in line with the ecosystem approach to aquaculture (EAA).

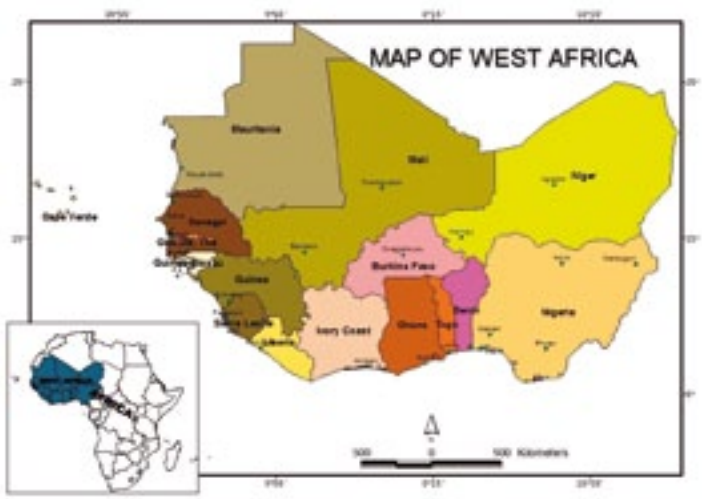
Aquaculture in West Africa

The West African Region comprises sixteen countries namely the Republic of Benin, Burkina Faso, the Republic of Cape Verde, the Republic of Côte d'Ivoire, the Republic of the Gambia, the Republic of Ghana, the Republic of Guinea, the Republic of Guinea-Bissau, the Republic of Liberia, the Republic of Mali, the Islamic Republic of Mauritania, the Republic of the Niger, the Federal Republic of Nigeria, the Republic of Senegal, the Republic of Sierra Leone and the Togolese Republic (Figure 1). It has a tropical climate with a population of around 300 million representing 4.6 percent of the world population.

Status of Aquaculture in West Africa

Aquaculture activities in the region are wide spread and have been practiced in the various countries for periods ranging from 40 to about 60 years. Levels of development and growth are quite varied. Production levels range from subsistence in rural communities to commercial in peri-urban centres. Countries with relatively strong aquaculture activities within the sub-region are the Federal Republic of Nigeria, the Republic of the Niger, the Republic of Ghana and the Republic of Côte d'Ivoire. Africa as a whole accounts for less than one percent of the world's aquaculture production (www.oecd.org/dataoecd/56/31/38523223.pdf). West Africa should therefore account for much less considering the fact that the Arab Republic of Egypt is the largest farmed fish producer in Africa. Fish production data for the study area in 2008 from capture and aquaculture are presented (Table 1).

FIGURE 1
Map of West Africa
(Inset - Map of Africa showing the location of the West African Region)



Source: http://wn.com/ECOWAS.

Aquaculture in the sub-region is largely undertaken in the freshwater environment, employing land-based and water-based facilities. Existing production systems include cages, pens, earthen ponds and concrete/fibre/plastic tanks. The most commonly cultured species are *Oreochromis niloticus* (Tilapia) and *Carias gariepinus* (Catfish). Others are trial productions of *Heterobranchus* and *Notopterus* sp, in the Republic of Sierra Leone (Sheriff, 2006).

TABLE 1
Fish production statistics for capture and aquaculture per country.

Country	Capture	Aquaculture	Total
Benin	37 495	180	37 675
Burkina Faso	10 600	405	11 005
Côte D Ivoire	58 000	1290	
Cape Verde	21 910	-	21 910
The Gambia	42 645	0	42 645
Ghana	34 9831	5594	355 425
Guinea	74 000	0	74 000
Guinea Bissau	6 750	0	6 750
Liberia	7 890	0	7 890
Mali	100 000	821	100 821
Mauritania	195 328	-	195 328
Niger	29 810	16078	45 888
Nigeria	541 368	143207	684 575
Senegal	447 754	200	447 954
Sierra Leone	203 582	0	203 582
Togo	20 000	126	20 126

Source: ftp://ftp.fao.org/fi/stat/summary/a-0a.pdf

Coastal aquaculture activities in the region are relatively few. Existing production activities include intensive production of *Chrysichthys nigrodigitatus* (Bagrid catfish) in lagoons in the Republic of Côte d'Ivoire (Sanogo, 2008), commercial production of *Peneaus monodon* (Black Tiger Prawns) in the Republic of the Gambia (FAO, 2007), and trial production of *Mugil* sp in the Republic of Sierra Leone (Sheriff, 2006) and a pilot project culturing *Epinephelus aeneus* (White grouper) has been reported in the Republic of Senegal. The Republic of the Gambia and the Republic of Côte d'Ivoire are also reported to have potentials for oyster production. While potential market for the product is yet to be identified in the Republic of the Gambia (www.accessgambia.com/information/aquaculture.html), production in the Republic of Côte d'Ivoire could not be continued because the product could not compete in price with wild stocks which are easily gathered from mangroves (Sanogo, 2008). Table 2 shows a list of other species reported to have been cultured in brackish water environments in the sub-region.

TABLE 2
List of Fish and shrimp species cultivated in African brackish waters.

Species Cultured	Côte d'Ivoire	Benin	Ghana	Nigeria	Senegal
Tilapia zillii	X		X		
T.rendalli	X			X	
T. nilotica	X		X	X	
T. galilaea	X		X		
T. guineensis	X	X	X		

Source: Coche, A.G. (ed) 1982. * Source: De Wilde and Gilles (2009).

Species Cultured	Côte d'Ivoire	Benin	Ghana	Nigeria	Senegal
T. melanotheron		X			
T. heudelotii	X				
S. m. heudelotti					X*
Mugil cephalus			X	X	
L. falcipinnis	X	X			
L. grandisquamis	X				
Chrysichthys walkeri	X			X	
C. nigrodigitatus	X	X		X	
Clarias lazera	X			X	
Penaeus duorarum	X	X	X	X	

Aquaculture site selection

Aquaculture sites selection is very important as it determines economic viability of a project by determining capital expenditure, running costs of production, mortality and ultimately, the success of the operation (Pillay and Kutty, 2005). Site selection is, however, complex involving identification of areas that are economically, socially and environmentally available, and offer the prospect to be commercially viable (McLeod, Pantus and Preston, 2002).

Site selection considerations vary based on the production system employed. For water-based culture systems (cages, pens, inshore and off shore culture systems) general site selection considerations include physico-chemical properties of the waterbody (temperature, salinity, oxygen, currents, pollution, algal blooms, exchange); weather, shelter, depth and substrate conditions, which ensure successful siting of cages. Other considerations are legal issues, access, land-based facilities, security economic and social considerations which relate to the establishment of the farm and profitability.

Basic site selection considerations for land based aquaculture (ponds, raceways, hatcheries, tanks etc.) include access, topography of the area, soil type, quality and quantity of available water as well legal issues. Sites for coastal pond farms should be tidal and intertidal mudflats in protected areas near river estuaries, bays, creeks, lagoons and salt marshes including mangrove swamps (Pillay and Kutty, 2005).

Regional and national factors relevant to site selection for aquaculture

Site selection considerations within the sub-region are based on the production system employed and are the same as those mentioned above for water-based and land-based systems. All the countries have, however, instituted some form of national legislation relating to environmental assessment and, which are based largely on general Environmental Impact Assessment (EIA) procedures. Although a number of these do not contain references to aquaculture, there is always the prospect of an aquaculture project being required to conduct some form of environmental assessment as part of site selection procedures (Nugent, 2009).

A summary of environmental law and EIA regulations likely to affect aquaculture site selection or practice in the sub-region are presented (Table 3).

In the Republic of Ghana the main legislative act governing site selection and the practise of aquaculture are: Fisheries Acts 625 of 2002 section 60 which requires licensing of aquaculture and recreational fishing projects, the Environmental Protection Agency (EPA) Act 490 of 1994 and the Environmental Assessment Regulations, 1999 (LI 1652) which gives mandate to the Agency to ensure compliance

TABLE 3
Summary of environmental law and EIA regulations affecting aquaculture in Africa (to 2006)

Country	Environmental Law	EIA regulations	Explicit mention of aquaculture in EIA	EIA oversight institution	Guidelines published for EIA: general or aquaculture
Benin	1999 Framework Law on Environment 98–030	2001	Simplified EIA mandatory for aquaculture/fish culture	ABE/BEA	General guidelines
Burkina Faso	1997 Law on Environmental Code 005/97	2001	Category A (requires EIA): dams over 10m height Category B (requires a notice of impact): - small dams between 3m and 10m height - construction of ponds for aquaculture	CONAGESE	
Cape Verde	Act No. 86/ IV/93 of 26 June 1993 defining environmental policy	2006		CAN	
Côte d'Ivoire	1996 Code on the Environment	1996		BEI/MLCVE, ANDE	
The Gambia	1994 National Environment Management Act 94/13	1999	EIA required: for storage dams, barrages, weirs; fisheries especially large-scale commercial projects;		General guidelines
Ghana	1994 Environment Protection Act 490/94	1999	EIA regulations: EIA mandatory for landbased aquaculture EIA for construction of dams/reservoirs Fisheries Act: EIA required to accompany any application for a licence for aquaculture; Fisheries Impact Assessments required for any activity impacting on a fishery (as well as EIA)	EPA	General guidelines
Guinea	1987 Code on the Environment	1990	EIA required: Aquaculture installations	Ministry	
Guinea-Bissau	1993				
Liberia	Environment Protection and Management Law	2002	mandatory for: 'artificial' fisheries (aquaculture for fish, algae, crustaceans, shrimps, lobster or crabs)	EPA	
Mali	1991 Protection of Environment and Life Framework 91–47	1999	EIA required: for dams and other permanent installations intended to retain or to stock water	Ministry	General guidelines
Mauritania		2004			
Niger	1998	2000	Indirect: EIA required for dams and reservoir	BEEEI	

Country	Environmental Law	EIA regulations	Explicit mention of aquaculture in EIA	EIA oversight institution	Guidelines published for EIA: general or aquaculture
Nigeria	Decree 58 of 1998 and Decree 86 of 1992	1992	EIA required: Land based aquaculture projects accompanied by clearing of mangrove swamp forests covering an area of 50 hectares or more; dams and man-made lakes and artificial enlargement of lakes > 200 ha	FEPA	General guidelines
Senegal	1983 Code on the environment	1983	Indirect: preliminary review for irrigation and small and medium agri-business.	Ministry	General guidelines
Sierra Leone	2000 Environmental protection Act	2008	EIA required: substantial changes in farming and fisheries practices e.g. introduction of new crops...; dams, drainage or irrigation projects…;	EPA	
Togo	1988 Code on the Environment	2006	Require EIA: dams and reservoirs (> 5ha < 10 ha: Simplified EIA, > 10 ha: In-depth EIA); Aquaculture/ Fish culture (< 300 ha: Simplified EIA, > 300 ha In-depth EIA). Extraction of water from rivers, underground, lakes, lagoons and the sea… for aquaculture, requires authorisation from the Ministry of Environment	Ministry	

Source: Nugent, 2009.

of all investments and undertaking with all laid down Environmental Assessment (EA) procedures in the planning and execution of development projects, including compliance in respect of existing ones.

The WRC Act 1996 (Act 522) which established the Commission, empowers it as the sole agent responsible for the regulation and management of the utilization of water resources in the country. The Commission does this through the granting of Water Rights, which has to be applied by an operator with an approved EIA document.

The principal legislation in the Federal Republic of Nigeria which probably makes EIA requirements for Aquaculture Projects necessary is Decree 86 of 1992, and for the Republic of Côte d'Ivoire Framework Act No. 96/766 of 3 October 1996 of the Code of the Environment. The EIA details the minimum content of any environmental study which covers; screening, mandatory study, mediation or review panel assessment; information required across the countries include:

- Description of proposed project area
- Description of existing environment
- Potential environmental impacts and alternatives
- Possible mitigation measures
- Environmental monitoring plans
- Provisional environmental management plans

- Consultations (Discussions with stakeholder)
- Decommissioning

One of the things these laws are intended to ensure is that aquaculture operations are located at sites where unacceptable ecological impacts such as low DO, high nutrients, destruction of biodiversity and important habitats would not occur or where they are likely to occur there are mitigation measures. Many of the EIAs so far carried out for aquaculture projects in the sub-region have, however, been for large commercial farms and this according to Nugent (2009) is because these have often received investment from private sources overseas or support from international agencies or banks and it is the expectation of their partners that EIA is part of the project installation, even where there may not have been comprehensive national legislation. Beside this for countries like the Republic of Ghana and the Federal Republic of Nigeria detailed EIA is limited to large commercial farms. In the Republic of Ghana fish farms considered to be small (no particular size defined) are only expected to register their operations with the EPA without the need for the submission of an EIA report and in the Federal Republic of Nigeria, only farms sizes larger than 50 ha are expected to submit EIAs prior to commencement and this virtually eliminates all existing farms (Nugent, 2009). Reasons for this practice probably being that small farms are assumed to have minimal impacts.

Use of models and Decision Support tools in aquaculture Site Selection

Geographic Information System (GIS) compared to existing aquaculture site selection procedures is considered one of the fastest and less expensive tools in aquaculture site selection, its use within the subregion for this purpose is, however, minimal. Available information on its use for this purpose are from studies carried out by Kapetsky (1994) and Aguilar-Manjarrez and Nath (1998) for the entire Sub-Saharan African area i.e. countries south of the Sahara Dessert. Both studies undertook an assessment of areas and locations with suitable to optimum potential for subsistence and commercial fish farming. The main difference between the two studies was in the resolution of data used; the later study using data of better resolution, making its outcomes more functional in assessing fish farming potential at the national level (Aguilar-Manjarrez and Nath, 1998). And more recently Asmah (2008) and Sankoh (2009) as part of doctoral research studies at the University of Stirling used GIS to determine aquaculture development potentials for the Republic of Ghana and the Republic of Sierra Leone respectively. All the studies so far undertaken focused mainly on development potential for freshwater pond culture. Asmah (2008) in her study briefly considered the potential for cage aquaculture development in the Republic of Ghana but the assessment was only based on the availability of a waterbody such as a lake or reservoir

The applications and relevance of GIS and remote sensing within the subregion must, however, be well appreciated as each of the countries had well established National Centres for Remote Sensing and Geographic Information Systems (http://nma.agirn.org/index.php/agencies/registered_agencies). The objectives of some of these institutions are to use GIS to maximize efficiency of decision-making and planning as well as training to individuals and other government institutions for a fee.

Carrying capacity estimates

Aquaculture growth involves the expansion of cultivated areas, higher density of aquaculture installations, increased feeds and other inputs. Being a resource-based activity, which competes for economic, social, physical and ecological resources with other industries, its development could have negative impacts on other industries such as fisheries, agriculture, and tourism with environmental impacts, which can have social and economic implications (FAO, 2008). Aquaculture ironically is sensitive to poor environmental conditions created by surrounding activities which can occur

as a result of natural and anthropogenic activities. The extent of the anthropogenic influences on the culture operations from without and within is dependent on what may be described as the carrying capacity of the ecosystem within which the aquaculture operation is located.

IUCN (2009) defined Environmental carrying capacity as the maximum number of animals or amount of biomass that can be supported by a given ecosystem for a given period of time. The term 'carrying capacity' according to the publication is often used in the context of coastal management or planning, with regard to human activities such as industry or aquaculture and is thought to be more appropriate for shell fish extraction. For other forms of aquaculture, the term 'holding capacity' is thought to be more appropriate as the concern in such cases is on the ability of the environment to efficiently absorb and assimilate excess loading of organic compounds and nutrients without any negative effects (IUCN, 2009).

Main tool for estimating carrying capacity is models and Decision Support tools.

Within the West African sub-region, no research on what constitutes carrying capacity, and how this relates to specific developments or sectors was found.

Main gaps and improvement needs according to the EAA

The Ecosystem Approach to Aquaculture is a strategy for the integration of the activity within the wider ecosystem such that it promotes sustainable development, equity, and resilience of interlinked social-ecological systems (FAO, 2010).

An important step in implementing the ecosystem approach to aquaculture (EAA) is the ability to work across administrative and ecosystem boundaries. The traditional methods of resolving aquaculture site selection by individual site assessment are length, intensive and subjective, and cannot be efficient if site selection is to be based on EAA.

Basic requirement for implementation of the EAA are spatial planning tools, including geographic information systems (GIS), remote sensing and mapping for data management, analysis, modelling and decision-making (FAO, 2010). Geographic Information System has the potential to incorporate and present information at different spatial scales and allows for effective management planning. GIS also makes it possible to assess multiple sites in a rapid and systematic way.

A first step needed to bring aquaculture site selection in the sub-region in line with the EAA principles is to create awareness of these principles, train stakeholders and relevant regulatory bodies on requirements of these principles and to equip relevant institutions with the necessary tools to be able to implement them. There may also be a need for enhanced coalition and development of institutional mechanisms to facilitate coordination among the various sectors with interests in the ecosystems where aquaculture operates.

Current site selection procedures in the sub-region are based on individual site assessment and which as indicated above could be lengthy and subjective. Although the environmental and social impacts of a single farm might seem unimportant, more attention must be paid to the potentially cumulative ecosystem effects of groups of farms at particular sites. This requires an ability to address the cumulative impacts of many small-scale developments probably through monitoring which is basic to effective environmental management of aquaculture.

Finally carrying capacity estimates is an important factor in sustainable aquaculture development and countries within the region should be educated to incorporate.

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Aquaculture in Southern Africa with special reference to site selection and carrying capacity issues

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Abstract

Growth in aquaculture production in Southern Africa has not kept pace with trends worldwide. Part of the reason for this decline includes significant barriers to entry for new aquaculture development, including problems with site selection and carrying capacity. Information on these constraints on aquaculture production in the region have so far been fragmented and this overview paper attempts to fill the gap through a desktop literature review of factors relevant to site selection and carrying capacity issues in southern Africa.The key regional and national factors for site selection are the degree of development, the need for favourable environmental conditions, the accessibility of sites, institutional constraints and the impacts of aquaculture of ecosystems in the region. Although environmental capacity is not a key concern yet on a regional level, several incidences of the impacts of pollution on freshwater aquaculture, bivalves and abalone are identified and remain a serious concern in certain aquaculture production systems in the region. The use of models and decisions support systems for better site selection and identification of carrying capacity issues are discussed in the developmental context of southern Africa and several recommendations are made. The expectation is that the results of this overview contribute to a better understanding on site selection and carrying capacity constraints to aquaculture production in southern Africa.

Introduction

With wild fish stocks declining at unprecedented rates worldwide, aquaculture production is seen as an important solution to provide food security and also meet protein and other dietary requirements. This is particularly important in Sub-Saharan Africa, with large portions of the population undernourished and dependent on both freshwater and marine fishing for livelihoods.

However, growth in aquaculture production in Southern Africa has not kept pace with trends worldwide. In fact, on the whole aquaculture production in the Southern African region has declined by on average 5 percent per annum over the past 5 years (Table 1). The two main producers in the region in 2003, namely the Republic of South Africa and the Republic of Namibia, have experienced significant declines in total production. Aquaculture production in the Republic of South Africa (the dominant producer in the region) has fallen from approximately 6 600 tonnes in 2003

to approximately 5 050 in 2008, a drop of more than 1 500 tonnes over 5 years. The Republic of Namibia's production has halved since 2003. The Kingdom of Lesotho by contrast has experienced strong growth, albeit from a low base.

TABLE 1
Total production (tonnes) for 2003 and 2008.

Country	2003		2008		Growth 2003–2008
	Tonnes	% share	Tonnes	%share	
Lesotho	4	0.1%	91	1.8%	86.8
Namibia	117	1.7%	58	1.1%	-13.1
South Africa	6 602	98.2%	5 049	97.1%	-5.2
	6 723	100.0%	5 198	100.0%	-5.0

Note: No aquaculture production was recorded for the Republic of Botswana and the Kingdom of Swaziland during this period.
Source: FAO Fishstat Plus

With the exception of the Kingdom of Lesotho, production does not appear to be positively affected by environment (Table 2). For the Republic of Namibia and the Republic of South Africa, both freshwater and marine aquaculture either stagnated or declined between 2003 and 2008.

At first glance indications are that the region has an abundance of potential aquaculture sites. For example, a recent bulletin indicated that in the Western Cape alone there are 2000 suitable dams that could produce up to 8 000 tonnes of fish per year. Furthermore, the Republic of South Africa's coastline is approximately 2 798 km long and the Republic of Namibia's coastline is 1 572 km which suggests ample scope for identifying coastal aquaculture sites. So why has production stagnated or declined in most parts of Southern Africa?

TABLE 2
Trends in aquaculture production (tonnes) per environment

Country	Environment	2003	2008	% growth
Lesotho	Freshwater	4	91	86.8
Namibia	Freshwater	15	15	0.0
	Marine	102	43	-15.9
South Africa	Freshwater	2 246	1 202	-11.8
	Marine	4 356	3 836	-2.5
	Brackish	-	11	
Total		6 723	5 198	-5.0

Source: FAO Fishstat Plus

Reasons for declines in aquaculture production

Identifying current and future issues and bottlenecks

There are a number of reasons why aquaculture potential has not been realized in Southern Africa. Part of the reason for the decline includes significant barriers to entry for new aquaculture development. These include the following:

1. Few individuals or communities have access to the capital needed to start up aquaculture projects, lack technical skills nor do they have links with the main players in the industry.

2. Difficulties in finding and acquiring an appropriate site for aquaculture production.
   a. Identification of freshwater aquaculture sites can be expensive and onerous. Traditional methods for site identification are haphazard and rely on word of mouth, visual inspections and follow up visits. Costs include the transportation costs and the time it takes to reach the sites. Geographic Information Systems (GIS) may help to reduce some of these site selection costs, but at the moment it is an underutilized resource (Steer, 2006).
   b. It can take years to rezone land for aquaculture activities, and in the sea there is no legal instrument for zoning offshore areas for aquaculture.

Typically, the development process may require an environmental impact assessment, land rezoning, public comment and meetings, and applications for various permits. Obtaining access to areas of water (outside of National Ports Authority controlled waters) for sea-based aquaculture is particularly difficult, as there is no legal instrument for the granting of a use right for this purpose.

3. With respect to land based aquaculture, access to land that has sufficient suitable water resources (fresh or sea water) for large-scale production may also be difficult to acquire. Even if the financing for a land-based operation is in place, finding suitable sites reasonably close to market exit points is often costly and difficult – this is particularly true for mariculture operations as a premium is placed on coastal land in the Republic of South Africa.

Value of aquaculture production

The value of aquaculture production in Southern Africa is dominated by a few key species (Table 3). For marine aquaculture, abalone production makes up almost 85 percent of the value of the Republic of South Africa's production, while for the Republic of Namibia it is approximately 50 percent. Bivalves make up an important minority, approximately 3.5 percent in the Republic of South Africa and 15 percent of value in the Republic of Namibia.

TABLE 3
Value of production by species, 2008

	Lesotho	Namibia	South Africa	South Africa % total
		Thousand US$		
Carps, barbels and other cyprinids	3	-	-	0
Salmons, trouts, smelts	630	-	3 470.0	8.3
Abalones, winkles, conchs		102	35 341.0	84.6
Miscellaneous freshwater fishes		28.5	453.6	1.1
Mussels			640.3	1.5
Oysters		35	854.3	2.0
Red seaweeds		27.9	247.7	0.6
Other	-	-	762.8	1.8
TOTAL	633	193.4	41 769.7	100.0

Source: FAO Fishstat Plus

In terms of freshwater production, the Republic of South Africa produced rainbow trout to the value of R44 million in 2003, the next highest being R11.8 million generated from freshwater shrimp (Steer, 2006). This high production value came from only 1750 metric tonnes of fish produced. In the Kingdom of Lesotho, aquaculture production includes trout and catfish, some for the tourist market and some exported to the Republic of South Africa for processing.

Regional and National factors relevant to site selection for aquaculture in southern Africa

A number of issues are relevant to aquaculture site selection in Southern Africa. Apart from the issues discussed below, Appendix A provides a checklist of criteria for aquaculture development.

Degree of development

Degree of coastal development has potential to conflict with mariculture development. Too much can conflict with aquaculture development (e.g. much of KZN coastline) although too little can also hinder aquaculture development (e.g. Wild coast). Furthermore, the absence of competing activities such as mining, tourism, polluting industries, domestic effluent, etc. that might conflict with aquaculture. Development can also bring the risk of poaching, vandalism and theft of equipment.

Favourable environmental conditions

These conditions determine the physical carrying capacity of an area (McKindsey *et al.*, 2006) – in other words the area of aquaculture activity that can occur in the available physical space.

Examples of geographic areas favourable for aquaculture production include:

1. Sheltered areas (harbours lees such as Port Elizabeth and Coega, lagoons such as Knysna, Langebaan). With the development of improved technology for sea cages, semi-sheltered area could also be considered for aquaculture (e.g. Walker Bay and Boegoeberg Bay near Alexander Bay). Deeper water is required for cage aquaculture of fin fish
2. Availability of kelp bed habitat (e.g. for abalone production)
3. Climatic and ocean conditions, including temperature, salinity, ocean depth and current flow
4. Availability of under-utilized coastline (e.g. Western Cape province)
5. For freshwater aquaculture, the availability of a suitable habitat for fish production. For example, trout farming requires a dam with surface area at least 15ha, a capacity of 150 000 m^3 or more, and a depth of 5 m or more (Steer, 2006). This is because if cages are not moved around during the season the water quality around the cages can deteriorate.
6. Furthermore, aquaculture farming will not be allowed in areas that are protected or environmentally sensitive (e.g. nurseries, bird sanctuaries, migration routes, etc.)
7. Area should be large enough to allow for rotation and for areas to lie fallow.

Accessibility

Accessibility includes:

1. The availability of transport infrastructure (such as a developed road network and proximity to airports)
2. Access to labour which includes proximity to urban settlements
3. Access to services such as freshwater, electricity, sewerage and communication infrastructure
4. Access to site specific requirements such as marine pumps, hatcheries, ponds, buildings, etc.
5. Access to major processors, major feed suppliers and major hatcheries

Institutional constraints

For example in the Republic of South Africa the only readily accessible waters for sea based aquaculture are the areas within the jurisdiction of Portnet which has total control of all activities in the waters surrounding its ports. Portnet leases

water for aquaculture at Saldanha Bay and Port Elizabeth. At present (2007) parliamentary approval is required for zoning of sea space for aquaculture outside of the Portnet areas of jurisdiction. In some cases this includes the use of Strategic Environmental Assessment (SEA) to determine where best to site aquaculture zones (e.g. The East Cape Development Corporation recently completed an SEA to identify suitable offshore aquaculture sites in the Eastern Cape Province). In addition the development process may require an environmental impact assessment, land rezoning, public comment and meetings, and applications for various permits.

Ecosystem impacts

The natural environment not only plays an important role in the physical scale of farming operations, but conflicts can occur between objectives that seek to maximize production capabilities, and environmental thresholds (environmental impacts that exceed the ecological carrying capacity). Site selection should exclude sensitive areas, MPAs, and other areas of recreation or tourism. Legal and institutional efforts to ensure that ecological thresholds are not exceeded can also affect site selection. Major issues include conflicts between endemic and exotic species, impact of farming practices, and animal health.

The balance between indigenous and exotic species

A number of issues are relevant for site selection:

1. The risk assessments required by the National Environmental Management Biodiversity Act for the use of exotic species are expensive and time consuming.
2. Fishery managers within the DEAT are in principle against the sale of cultured indigenous species on the local market as they maintain they can be used as a front for the sale of wild poached product.
3. Permits are required for cultivation of freshwater species such as trout. These may be difficult to obtain.

Impact of species and farming practices on ecosystem balance, water quality and environmental health

The abalone industry funds its own water quality management programme and health management programme, but smaller aquaculture SMEs cannot afford this.

The SABS and government require frequent water quality and product testing. While the costs of this can be absorbed by large and medium size enterprises, the cost (typically over R 100 000 per year) is simply too high for small enterprises.

One way in which environmental impacts are mitigated is through integrated multi-trophic aquaculture (IMTA). An example where this is applied in the Republic of South Africa is through implementing IMTA with the seaweed *Ulva lactuca* L. and the abalone Haliotismidae L (Nobre *et al.*, 2010). IMTA results in improved productivity of abalone, allows for water recirculation and reduces abalone effluent discharge into the environment, and also allows farms to function without the need for access to the ocean for periods of time. The latter is particularly useful in cases of oil spills or red tides.

Health management of farmed stocks.

Aquaculture veterinary services are most rudimentary and most farms have stock (herd) health management schemes. Disease and drug free certification is a HACCP requirement for the export of products to the European Union. Aquaculture activities should avoid areas associated with algal blooms (if possible).

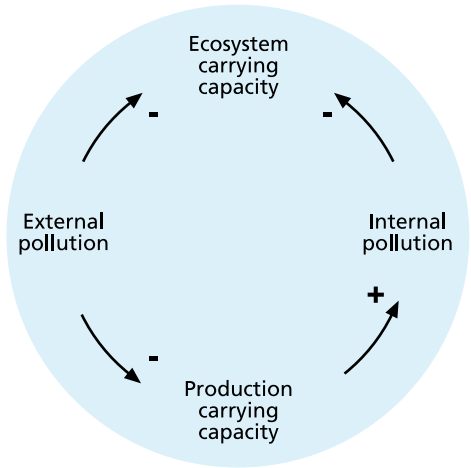
These and other issues indicate the importance of an ecosystem approach to aquaculture (Soto, Aguilar-Manjarrez and Hishamunda, 2008).

Environmental carrying capacity issues

An important relationship exists between pollution and carrying capacity (Figure 1). An increase in external pollution (pollution from non-aquaculture sources) reduces both ecosystem carrying capacity as well as production carrying capacity. An increase in production carrying capacity has the potential to increase aquaculture related pollution, which in turn reduces the ecosystem carrying capacity via impacts on ecological integrity.

In certain cases, however, an increase in external 'pollution' may have a positive impact on production carrying capacity. An example is the "culture based fishery" characteristic of many Southern African inland fisheries (Rouhani and Britz, 2004). This is a form of extensive aquaculture that resembles a fishery where the volume of fish produced per unit area is low but input running costs are also very low. Fish rely on natural production in a pond as their primary source of food (just as they would in a fishery); however, natural production in the pond may be enhanced by adding animal manure to the water, which increases the carrying capacity of the pond.

FIGURE 1
The relationship between ecosystem carrying capacity and pollution



A number of coastal ecosystems in Southern Africa are particularly vulnerable to both internal and external pollution, notably estuaries, which also provide favourable conditions for the establishment of aquaculture activities (e.g. Knysna). A number of indicators may be used to assess ecological integrity of marine ecosystems (Borja *et al.*, 2008): freshwater requirements of estuaries, fish, estuarine health or conservation significance. The emphasis is on developing technologies that improve production that also preserve the ecological integrity of the environment (Brummett and Williams, 2000).

Freshwater aquaculture

The introduction of trout, and especially rainbow trout in Southern Africa, is associated with a number of adverse effects. The first issue related to the impact of trout species themselves on endemic fish populations through competition and predation (Cowx, 2002). In Europe the introduction of rainbow trout has resulted in the reduction of native salmonid populations in Lake Ohrid, Macedonia. Furthermore, there are reports of rainbow trout escaping from farms into rivers and decimating the endemic fish stocks, particularly through predation of the juveniles. Secondly, *Oncorhyncus mykiss* displaces endemic species through aggressive behaviour and alters the fish community structure. In the Republic of South Africa there are problems on rivers where trout have been introduced and have resulted in degradation of the endemic species communities.

The second issue relates to the effects of trout farming practices on ecosystems. For example in a study in Southern California, effluent concentrations downstream of the trout farm were 1.7 times higher than the reference site (Pachon and Walton, 2008). Algal abundance, suspended particulate matter and ammonium nitrogen concentrations were also higher. It should be noted however that this was a small desert stream and conditions are likely to differ where runoff is higher.

Bivalves

Work on Bivalves indicates a number of adverse environmental impacts that can affect ecological carrying capacity. On the one hand these are associated with specific aquaculture activities (See Appendix B). A summary of some of the key issues is provided in Inglis, Hayden and Ross (2000). These include:

1. Organic enrichment of sediments below the farmed areas by faeces and pseudofaeces;
2. Shifts in benthic food webs from predominantly suspension-feeding to deposit-feeding faunas;
3. Shading of submerged plants and animals by surface infrastructure;
4. Drop of shells and other waste materials;
5. Localised depletion of phytoplankton from surface and sub-surface waters; and
6. Attraction of predators, such as starfish and fish.

The presence of mussels (*Mytilus galloprovinvialis*) and foulers associated aquaculture activities (such as the sea squirt, *Ciona intestinalis*) results in a high rate of sedimentation from faeces, pseudofaeces and fallen mussels. In a study conducted on an 80 hectare mussel farm in Saldanha Bay, the sedimentation rate within the farm was found to be high with 300 kg organic carbon/m^2/year (300 percent of ambient) and 45 kg nitrogen/m^2/year (200 percent of ambient) (Stenton-Dozey, Jackson and Busby, 1999).

Abalone

Although abalone farming represents an intensive flow-through system, it releases, compared to e.g. fish cage farming, only limited amounts of nutrient wastes (Troell *et al.*, 2006). The main reason for this is feeding mainly kelp or feeds with low fishmeal content. Due to the high-energy coasts of the Republic of South Africa, with massive mixing and naturally high levels of upwelled nutrients, nutrient effluents from farms most likely have insignificant effects on the coast.

However, the former Department of Water Affairs and Forestry has produced water quality guidelines for coastal marine waters that are intended for protection of the natural environment. A preliminary study characterising effluents from seven west coast abalone farms (Samsukal, 2004 cited in Troell *et al.*, 2006) concluded that dissolved nutrients were in accordance with the recommended standards outlined in the former Department of Water Affairs and Forestry water quality guidelines. The particulate loading (sizes less than 63 µm) was, however, found to be significant, as were the numbers of herbivorous crustaceans released from the farm during cleaning. The implications of this for the environment were, however, not studied. A preliminary study by Potgieter (2005, cited in Troell *et al.*, 2006) showed that approximately 100 kg of particulate waste per tonne of abalone is released annually from tank cleaning operations. This is a significant release but many times less than fish cage farming. Any effect from such release is probably of local nature.

The tube-dwelling polychaete worm *Terebrasabella heterounicinata* affects abalone growth negatively and it can occur in high densities at farms. It is not known if effluent from polychaete infested farms increase the infestation rate for wild abalone living in close proximity to the farm.

Use of models and decision support tools

GIS software can serve as a useful guide to site selection, and may reduce some of the costs associated with site selection. However, the human element associated with site selection cannot be eliminated. A study utilized GIS techniques to identify suitable sites for trout farming in the Western Cape. Of a total of almost 1500 dams, only 21 dams (1.4 percent) were found to be suitable (Steer, 2006). Furthermore, the study

found that a number of successful aquaculture sites would have been screened out if based solely on this approach.

GIS is also widely used in carrying capacity model (McKindsey *et al.*, 2006). Decision support tools generally utilize an integrated approach that utilizes a combination of approaches such as fine scale circulation models, broader ecological models, databases such as GIS and individual based models (an example of this is the SIMILE project in Northern Ireland).

There are at least two problems with decision support models. The first is that these are often costly, complex and impractical. This is particularly problematic in a developing country context. A second problem with decisions support tools is that the carrying capacities are not precise values but are rather subject to large uncertainties.

The first problem is addressed through the use of an "Expert System," namely the development of a library of information and tools to provide the best possible advice to decision-makers even when experts in the relevant fields are not available. An Expert System is a computer package that contains a large database of information applicable to the problem at hand along with models and other programs for manipulating these data in order to provide meaningful advice to decision-makers. Expert Systems are designed through consultation with experts in the field in order to provide advice similar to what the experts would advise if they were available.

The problem of imprecise values is sometimes addressed through the use of a Fuzzy Expert System. The outputs in this case are not precise numbers but rather functional relations between production levels and acceptability. In other words, instead of saying that the carrying capacity has some value X, meaning that production levels below X are totally acceptable and levels above X are totally unacceptable, we say that a production level of X is 50 percent acceptable, while higher or lower values would be assigned acceptabilities of, say, 15 percent or 80 percent.

Fuzzy logic tools have been used to some extent in fisheries management in the Republic of South Africa (e.g. Paterson *et al.*, 2007).

Recommendations

A summary of issues and associated recommendations is included in Appendix C.

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Appendix A: Aquaculture site selection questionnaire

The following checklist of questions is provided as a self-guiding primer for the would-be farmer.

Economic Questions:
Do you have a realistic business plan containing all relevant information required by financial and government institutions for speedy approval?
Can you secure sufficient capital at a reasonable interest rate?
Does your management team have sufficient management and financial skills to help manage the farm?
Have you made a realistic assessment of the timing and scale of expected returns on your investments?
Do you have adequate cash reserves for unanticipated costs such as equipment and/or crop loss?
Are you aware of the various government grants/schemes available?
Site selection:
Is the proposed site in a region zoned as suitable for aquaculture?
Does the site have a site-topography suitable for proposed design?
Does the site have sufficient and acceptable water supply?
Is there adequate room for intended use plus future expansion?
Does the site have acceptable potential for effluent disposal?
Does the site have a climate suitable for the intended species (which should be natural to the area)?
Is the access to services, technical assistance and public infrastructure such as roads?
Species selection:
Is the species suited to the local climate conditions/extremes
Is it native to the area and have you consulted the authorities/Biodiversity Act?
Do you understand the basic needs of the species in order to build it into management plans?

Have you been in touch with an industry representative about information change?
Is there a market for your species (local or international)?
Have you explored the various production strategies available?
Do you or your business partner have the necessary technical experience? If not, are you prepared to employ someone who does?
Are you intending to spawn and grow? If not, are dependable sources of juveniles readily available locally?
Market intelligence:
Have you identified your market and will you be able to supply at demand the required quality?
Have you examined the existing situation with respect to market size and demand, along with the level of competition?
Have you determined the form in which you will market your product and are you aware of the required standards?
Can you supply product to your market on a regular basis throughout the year?
Do you have the means to harvest, handle hold and transport the product?
Socio-legal considerations:
Is the development of an aquaculture facility at your site acceptable to neighbours/ community and other who may use the region?
Have you discussed your plans with the relevant government authorities?
Are you aware of the required permits to be obtained, can you obtain the permits for an extended period of time or do they have to be renewed frequently?
Is the development of an aquaculture facility at your site acceptable to neighbours/ community and other who may use the region?
Have you discussed your plans with the relevant government authorities?
Are you aware of the required permits to be obtained, can you obtain the permits for an extended period of time or do they have to be renewed frequently?

Source: Aquaculture Institute (www.ai-sa.org.za)

Appendix B: Selection of activities related to bivalve culture that may influence the ecological carrying capacity of a coastal area

1. Seed collection

a. Dredging
- i. Disturbance of benthic communities, especially the removal of long-living species
- ii. Removal of juveniles from wild populations of target species
- iii. Collection of non-target species
- iv. Suspension of sediments
- v. Release of H2S and reduction of dissolved oxygen in the water due to oxygen-consuming substances, release of nutrients

b. Artificial collectors
- i. Removal of juveniles from wild population of target species
- ii. Increasing target and no-target species recruitment success
- iii. Alteration of the hydrodynamic regime
- iv. Acting as FAD
- v. Risk of entanglement for large vertebrates (e.g. marine mammals, sea birds, turtles, sharks).

c. Hatcheries
- i. Chemical pollution (e.g. pharmaceuticals)
- ii. Genetic selection
- iii. Spread of diseases

d. Importation
  i. Introduction of alien species
  ii. Genetic pollution
  iii. Spread of diseases

2. Ongrowing
a. Effects common to all techniques
  i. Organic enrichment of seafloor
  ii. Providing reef-like structures
  iii. Alteration of hydrodynamic regime (current speed, turbulence)
  iv. Food web effects: competition with other filter feeders, increasing recycling speed of nutrients, removal of eggs and larvae of fish and benthic organisms
  v. Spawning: release of mussel larvae
  vi. Providing food for predators of bivalves
  vii. Control of predators and pests
b. Bottom culture
  i. Activities to prepare the culture plots, e.g. dredging for predator removal
  ii. Removal of associated organisms by dredging and relaying
c. Artificial structures (trestles, poles, rafts, longlines)
  i. Acting as artificial reef or FAD (attraction/displacement or enhancement of animals)
  ii. Risk of entanglement for big vertebrates (e.g. marine mammals, sea birds, turtles, sharks)

3. Harvesting
a. Effects common to all techniques
  i. Removal of biomass, nutrients
  ii. Removal of non-target species
  iii. Competition with predators
b. Dredging
  i. Disturbance of benthos communities, especially removal of
  Long-living species
  ii. Suspension of sediments
  iii. Release of H2S and decrease of dissolved oxygen in the water due to oxygen-consuming substances, release of nutrients
c. Collection of off-bottom structures
4. Processing
a. Dumping of by-catch
b. Relaying near auction houses
c. Depurating
d. Dumping of shells
e. Effluents from processing plant
f. Spread of alien species or diseases

Source: McKindsey et al., 2006.

Issue	Recommendation
Lack of st-art up capital	The establishment of Public-Private-Partnerships (PPPs) to involve SMMEs in sustainable forms of aquaculture. This model could also be utilized to develop aquaculture in rural areas (through CPPPs). The SMME development programme could be achieved in two ways; 1. A private investor contributes financial and technical skills while the community provides resources (land/water, labour etc); and 2. Government could provide funding for the community per cent share in the venture, the private company provides technical skills and some of the funding. The community will provide resources such as labour or land/water if possible.
Site selection expensive and time consuming	A key intervention by government should thus be facilitated access to suitable sites to stimulate investment into the sector. In in order to streamline and facilitate mariculture development in the Republic of South Africa, a sector planning process identified eight potential aquaculture development nodes. The potential mariculture nodes identified included Port Nolloth and Kleinsee in the Northern Cape Province, Toothrock, Saldanha Bay and Mossel Bay in the Western Cape, Coega (Port Elizabeth), the East London IDZ in the Eastern Cape, and Amatikulu in Kwa-Zulu Natal. Benefits accruing from the proposed clustering of mariculture projects into nodes would include: • Readily available, partially developed sites, which would minimize land preparation costs; • Basic on-site infrastructure (electricity and other municipal services); • Ready access to a source of seawater or fresh water; • Lower individual operating costs – through shared resources, marketing and support services, thereby achieving economies of scale; • On-site expertize, in the form of scientific support or practical experience from the other operations in the park; • On-site staff training programmes supported by R&D personnel; • A limited requirement for an environmental impact assessment (EIA), since a general assessment would have already been conducted for the park.
	In the freshwater arena, no sites for "aquaculture development zones" (ADZs) have as yet been identified, however it is expected that some of the old state run hatcheries such as Dzindi and Turfloop (Limpopo) and Lydenburg (Mpumalanga) could be developed into ADZs.
Ecosystem approach to aquaculture	The ecosystem approach to managing watersheds, with the rivers, wetlands, lakes, estuarine areas, and land viewed as part of a continuum, is fundamental to managing water for inland fisheries. This approach should consider not only water quantity and quality but also the connectivity of the system because many species of fish must be able to move between spawning, nursery, and feeding areas within a basin. This management approach needs to consider land-use practices, such as agriculture and forestry, as well as the needs of industry, urban areas, and waterborne transport that affect basin processes and the quality, quantity, and timing of flows. The approach is further complicated by the fact that many river basins are transboundary and may be located within several countries, necessitating international mechanisms to regulate and manage river flows.
Impact of trout on endemic species	The introduction of trout can be justified if the habitat it is introduced is isolated and holds no endemic or endangered species.
Impact of trout effluent on carrying capacity	Intensive running water culture systems need constant inputs of high-quality water to ensure sufficient oxygen for the fish and removal of wastes; sufficient flow is needed in rivers into which farm effluents are discharged to dilute wastes and nutrients without damaging ecosystems.
Risk assessments for the use of exotic species expensive. Permits difficult to obtain	Develop guidelines on the use of exotic species, which species are acceptable, where they can be farmed and under what conditions. Consideration should thus be given to a grant from government to undertake risk assessments in areas earmarked for strategic aquaculture development.
Cultured indigenous species may be used as a front for the sale of wild poached product	Traceability and certification schemes to market indigenous species on the local market. Government should be proactive in developing traceability schemes to open local markets for producers.
Fish health and the risk of diseases	Reduce fish stress as far as possible e.g. through maintaining correct stocking densities and environmental conditions Strict control over the importation and introduction of stock to reduce risk of disease accompanied by routine monitoring and application of disease management protocols

Aquaculture site selection and carrying capacity management in the People's Republic of China

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Abstract

Fisheries have provided about 1/3 of animal protein to 1.3 billion Chinese people, and made significant contribution to improving Chinese living standard and food security. As the largest aquatic food producer in the world, the People's Republic of China has exploited most of its waterbodies and land that suitable for aquaculture. This paper has reviewed the aquaculture site selection and carrying capacity management status in the People's Republic of China. Factors relevant to aquaculture site selection in the People's Republic of China include functional zoning scheme of local land and water areas, water and other environmental quality requirements, influence to local environment and the influence to community welfare. Local issues like such as carrying capacity farming, environmental pressure and deterioration caused by industrialization, rapid expansion of inland freshwater shrimp farming and predicament in the aquaculture related law enforcement are identified as major problems related to the sustainable development of aquaculture. The status of virtual tools (e.g. databases, models) usage and factors related to EAA in the People's Republic of China are also analysed. The continuous increasing of fed animals' portion in the aquaculture structure indicates it is weakening in net food production and increasing environmental pressures in the People's Republic of China's aquaculture industry. Problems in water area zoning scheme enforcement, lack of effective monitoring and legislation on aquaculture effluent discharge are the current bottlenecks limiting reasonable aquaculture site selection and carrying capacity management in the People's Republic of China, and some relevant recommendations have been provided.

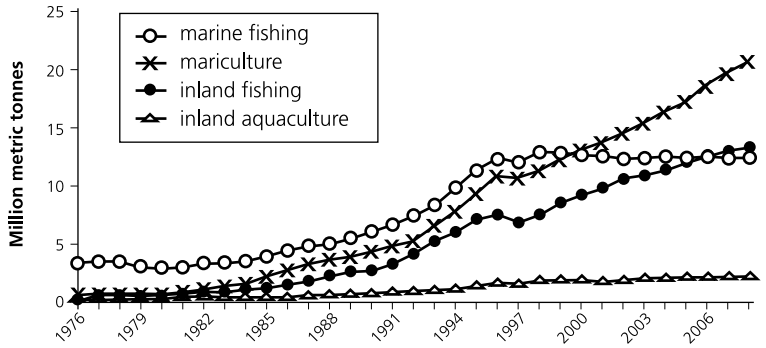
Introduction

The People's Republic of China has the largest aquaculture sector in the world in terms of both the volume of aquatic animals produced and the number of species cultivated. In 2006, the People's Republic of China contributed 67 percent of the world's supply of cultured aquatic animals and 72 percent of its supply of aquatic plants (FAO, 2009).

Status and trends of aquaculture in the People's Republic of China

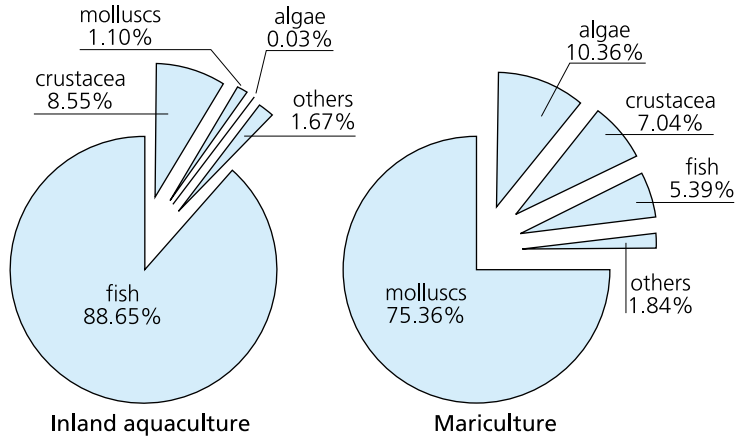
Since 1982 aquaculture in mainland of the People's Republic of China has been developing rapidly, the production of aquaculture has overrun the production of capture, and the production of mariculture has overrun marine fishing (Figure 1). Due to over fishing in inland and coastal waters, fisheries increment in the People's Republic of China (PRC) will mainly come from aquaculture in the near future.

FIGURE 1
Fisheries Production in China (mainland, tonnes)



Source: Fisheries Bureau, Ministry of Agriculture, PRC (2009).

FIGURE 2
Aquaculture production and composition of China in 2008



Source: Fisheries Bureau, Ministry of Agriculture, PRC (2009).

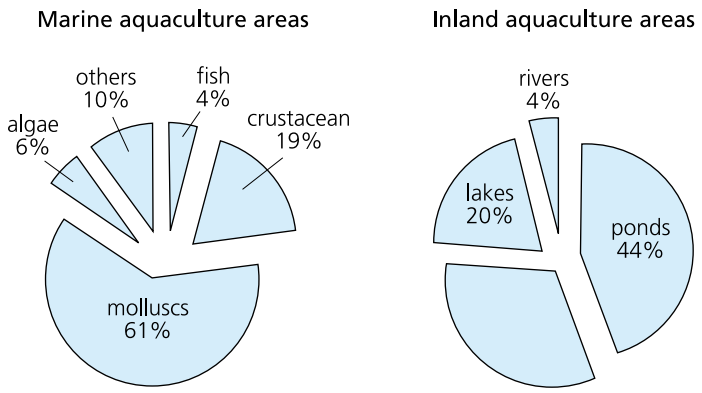
In 2008 the aquaculture production of the People's Republic of China was 34.1 MMT, in which inland aquaculture took 61 percent (Fisheries Bureau, Ministry of Agriculture, PRC, 2009). It can be seen (Figure 2) that molluscs (75.2 percent) are the main component of mariculture production and fishes (88.6 percent) are the main component of inland aquaculture production. The People's Republic of China produces 77 percent of all carps (cyprinids) and 82 percent of the global supply of oysters (ostreids) (FAO, 2009). In general, aquaculture in the People's Republic of China is a high ecological efficiency industry because of the high production of low trophic level carps (freshwaters) and molluscs (marine). Fisheries have provided about 1/3 of animal protein to 1.3 billion Chinese people, and made significant contribution to improving Chinese living standard and food security (Dong, 2009).

Factors relevant to site selection for aquaculture in the People's Republic of China

The People's Republic of China has a long history of aquaculture, particularly for inland freshwater aquaculture, which began 3000 years ago. In the People's Republic of China, the most important inland aquaculture sites are ponds, reservoirs and lakes, respectively contributed 70.4 percent, 11.6 percent and 7 percent to the total inland aquaculture output. Mariculture takes place in three forms: in the sea, on mud flats and land based (ponds), contributing respectively 50.3 percent, 38.5 percent and 11.2 percent to its total marine output in 2008 (Fisheries Bureau, Ministry of Agriculture, PRC, 2009). The area distribution of mariculture and inland culture (mainly fish) is shown in Figure 3, which indicates that shellfish culture covers the biggest area in the sea, and ponds are the most important fish farming measure in freshwater culture.

There is not a special law or legislation on aquaculture site selection in the People's Republic of China, but relevant provisions exist in many comprehensive laws and regulations dealing with fisheries and aquatic environments, including Fisheries Law of PRC (1986, 2000, 2004), Regulator Law for Sea Area Usage (2001), and over 25 legislative instruments (Zhijie, 1989; Cao and Wong, 2007) addressing issues such as regulations on Water Quality Standard for Fisheries (GB11607–1989), Sea Water Quality Standard (GB3097–1997), Environmental Requirements for Origin of Non-environmental Pollution Aquatic Products (GB/T 18407.4–2001), Water Drainage Standard for Mariculture (2007), Requirement for Water Discharge from Freshwater Aquaculture Pond (2007), Marine Protected Areas (1994, 1995, 1997), Environmental Impact Assessment (2002) (Lindhjem *et al.*, 2007), and the implementation of the UNCLOS Convention in 1998 (Keyuan, 2001). In general, there are four main factors affecting aquaculture site selection in the People's Republic of China:

FIGURE 3
Area distribution of mariculture and inland aquaculture of China in 2008



Source: Fisheries Bureau, Ministry of Agriculture, PRC (2009).

Functional zoning scheme of local land and water areas

All the land and water areas in the People's Republic of China are state owned, so the use of land and water area (e.g. aquaculture) must fit the local functional zoning scheme. For example, Functional Zoning Scheme of the Coastal Areas of Guangdong Province was issued in 1999 (People's Government of Guangdong Province, 1999), which specified the coastal area into different function zones, functions for the zones included: natural resources protection, industry, harbor, aquaculture, sewage draining, etc. In 2004, Aquaculture Planning for Inland Water Area and Coastal Zone of Guangdong was approved by the provincial government, which setup the guideline for the aquaculture development and management of local authorities. In order to fulfill such regulations, the aquaculture farm license provision came into force since 2002; license became the precondition for any new farm development since then, and old farms were also requested to post-register the license in a given period.

Water and other environmental quality requirements

Water quality and other environmental factors requirements are also established in those aquaculture related laws and regulations of the People's Republic of China. For example, the Water Quality Standard for Fisheries (GB11607–1989) specified the water quality requirement for aquatic animals and plants growth and reproduction. Along with increasing international communication on food quality safety and legal system development since 1990s, regulations such as Sea Water Quality Standard (GB3097–1997), Environmental Requirements for Origin of Non-environmental Pollution Aquatic Products (GB/T 18407.4–2001), Water Quality Standard for Mariculture (NY 5052–2001), Water Quality Standard for Freshwater Aquaculture (NY 5051–2001) etc. have formulated more detailed environmental requirements for new and existing aquaculture farms, and they co-act with the farm license system.

Influence on local environment

The People's Republic of China enforced Environmental Protection Law in 1989, Marine Environmental Protection Law in 2000; more and more standards addressing the environmental influence of aquaculture farms such as Water Drainage Standard for Mariculture (SC/T 9103–2007) and Requirement for Water Discharge from Freshwater Aquaculture Pond (SC/T 9101–2007) came into force in recent years. These are the legal restriction on the aquaculture farm construction, running and discharge, which inevitably relate to site selection.

Traditional fish farms in the People's Republic of China are mostly typical polyculture including integrated multi-trophic aquaculture (e.g. inland polyculture of carps; marine shellfish-macroalgae polyculture, etc) or combined with other agricultural sectors such as rice and mulberry fields, the negative environmental cases are seldomly reported. However, the development of intensive farming (e.g. intensive shrimp farming, fish cage farming etc.) since recent years has brought prominent threats to the environment, e.g. fish cage farming in reservoirs and lakes (Ning and Gu, 2004; Ning *et al.*, 2006; Sun *et al.*, 2005) and coastal areas (Wang, Wei and Wen, 2006; Gan *et al.*, 2006; Ge, 2009).

Influence on community welfare

Aquaculture is not only important in ensuring the People's Republic of China's food security in the nation wide, but also important to the community livelihood and welfare locally. There are presently 5.04 million farmers working on this industry (inland and marine). Economic benefit and risk are the predominant factors affecting the decision of new farm construction (including site selection) or shutting down the old farms for the stakeholders.

Continuing industrial development in the People's Republic of China in the recent decades and rural population migration to the coast has led to dramatic increases in nitrogen and phosphorus loading resulting in degradation of coastal water quality and proliferation of HABs (Guo *et al.*, 1998; Hao, Huo and Yu, 2000; Shen, 2001), which has brought serious challenge to the profitability of local aquaculture. For example, the rapid industrialization in the west coast of Shenzhen swept away all the aquaculture farms in late 1990s which had been the main economic source of local people 30 years ago, and the famous Shenzhen Shajing Oyster is left only in the memory of old local people (http://gzdaily.dayoo.com/gb/content/2001-03/06/content_80465.htm). On the other hand, Shenzhen is now the special economic zone of the People's Republic of China, a modern industrial metropolis.

Identifying issues locally specific to species, cultures, and geographies

Farming in excess of the carrying capacity

Although the People's Republic of China has the largest aquaculture industry in the world, there are very few large-scale aquaculture corporations domestically; most of the production comes from millions of small-scale farms owned by individual farmers, which brings the difficulty in coordinating farm scales and distribution for the local fisheries administrative authorities. Rapid growth of aquaculture production in the People's Republic of China prompted by technical progress (e.g. commercial feeds, aerator using, etc.) since the late 1990s has dramatically improved the living standards of part of aquaculture farmers, which has also caused the immoderate expansion of farming scale (Dong, Pan and Li, 1998), over carrying capacity farming has become a common failing in many coastal and inland systems. For example, Sandu Bay (26°35'11"N, 119°47'05"E) is a small semi-enclosed bay (263 km^2) in Fujian Province, which was the original natural distribution area of yellow croaker (*Pseudosciaena crocea*); yellow croaker cage farming started in some coastal regions Sandu Bay in 1995, in which Qingshan region was the main cage farming area, and the bay was soon

overloaded (Figure 4a,b,c,d). There were about 1000 fish cages in Qingshan in 1996, but the cage number in this region soared to 50 000 in 2005, and at the same time the total cage number in Sandu Bay turned to 260 000. However, the mass expansion of farming scale has not brought mass benefit, but frequent outbreaks of anoxia, HAB, epidemic fish diseases and mass mortality since then (Fang, 2008; Zhang, 2008). Similar problems also happened to other economic species, such as pearl oyster farming in the Guangdong and Guangxi coast of Beibu Gulf (Fu *et al.*, 2009).

FIGURE 4a
Fish cage farming locations in Sandu Bay

Source: Zhang (2008).

FIGURE 4b
Satellite image of fish cages in Qingshan Region, Sandu Bay

Source: Image © 2012 Digital Globe.

Environmental pressure and deterioration caused by industrialization

The strong development of the Chinese economy, centred mainly on manufacturing, together with the influx of rural populations to urban areas, many of which are located in the coastal zone or near major rivers, have resulted in a substantial increase in nutrient loads, leading to great environmental pressure and deterioration, such as pollution, frequent occurrence of HAB and fish kills etc. (Guo *et al.*, 1998; Hao, Huo and Yu, 2000; Shen, 2001; Xiao *et al.*, 2007). The environmental conditions in many areas are no longer suitable for aquaculture, e.g. the coastal areas of Yangtze River Estuarine and Hangzhou Bay. Both these areas were traditionally important aquaculture bases for Shanghai and nearby cities, but the water environment in the areas were polluted in varying degrees by inorganic nitrogen, organic substances, phosphorus, petroleum and heavy metals, and the contents of all these pollutants had exceeded the standard of fisheries water quality or the first category of seawater quality standard of the People's Republic of China by 2003 (Zang *et al.*, 2003). Red tide and anoxia are the other two typical symptoms in current Yangtze River

FIGURE 4c
Closer satellite image of fish cages in Qingshan Region, Sandu Bay

Source: Image © 2012 Digital Globe.

FIGURE 4d
Fish cages in Qingshan Region, Sandu Bay (2008)

Source: Zhang (2008).

estuarine. There were only 9 red tides occurred in the coast of the People's Republic of China in 1970s, 74 in 1980s, then shifted to 20–30 annually in 1990s, surprisingly the occurrence of red tides in Yangtze River estuarine was 48 in the first six months of 2002, and the affected area was more than 5 000 km^2 (Chen, 2008).

Rapid expansion of inland freshwater shrimp farming

Inland shrimp farming started in the People's Republic of China in the late 1990s, and it was initially developed to reclaim the saline and alkaline wasteland in some coastal and inland areas using local natural low salinity groundwater (Zhu and Dong, 2005). However, the great tolerance to low salinity of the Pacific white shrimp (*Litopenaeus vannamei*) has led to the rapid expansion of shrimp farming to many traditional freshwater agricultural areas since 2001, and it has become an efficient way to increase farming profit (Zhu *et al.*, 2004). In the freshwater area, farmers add salt into the water to keep the salinity at around 3 ppt (He and Wang, 2006). However, in this "freshwater" situation, *L. vannamei* survives better and grows faster at higher salinity, so more and more salt is added by the farmers. By the end of 2008, freshwater shrimp (*L. vannamei*) farming was present in 26 Chinese provinces, and the inland shrimp production in the People's Republic of China was 542 000 tonnes in 2008, while the *L. vannamei* mariculture production was only 520 000 tonnes (Fisheries Bureau, Ministry of Agriculture, PRC, 2009).

Adding large amount of salts into freshwater area could bring disastrous ecological consequences such as land and water salinization, which could even threaten the food security (Zhu and Dong, 2005; Liu and Wan, 2007), similar problems happened in the Kingdom of Thailand in the 1990s (Braaten and Flaherty, 2001), but the potential risk of such activity seems not been realized by relevant agricultural authorities; on the contrary, rice field *L. vannamei* culture is being encouraged by many local fishery agencies around the People's Republic of China (Wang, 2005; Yang, 2009; Zhang, 2009).

Predicament in the aquaculture related law enforcement

Most of the aquaculture farms in the People's Republic of China are located in the rural and suburban area, where local economic condition is not as good as in the cities, and economic development is likely the primary goal of most of the local governments. Aquaculture as an important economic activity is always favoured by the government, so sometimes the unlawful act such as over carrying capacity farming and waste water discharge without treatment are not strictly stopped (Liu *et al.*, 2008). Problems also exist in the legal system itself. For example, the present aquaculture related laws and regulations (e.g. Fisheries Law of PRC) are mostly guidelines and framework for management, which lack practical punitive measures (Liu *et al.*, 2008). Up to now, the pre-construction environmental influence assessment is lacking for new farms (Luo, Zhu and Bao, 2009), and aquaculture effluent fee is still not legally adopted in the People's Republic of China (Dong, 2009).

Use of models and Decision Support tools

Scientific databases such as the People's Republic of China Marine Science Database and South China Sea Marine Science Database have been developed by the institutions of the Chinese Academy of Science (CAS) and available for scientific research and decision-making since 2005 (Huang and Li, 2006).

Modern virtual technologies such as remote sensing and modelling for aquaculture management and ICZM were introduced to the People's Republic of China during the late 1990s through a series of collaborative projects with Europe and North America. Knowledge transfer through these international programs led to the application of some of the Decision-Making tools such as the MOM model for Sanggou Bay (Zhang *et al.*, 2009), the EcoWin2000 and FARM models in Sanggou Bay and Huangdun Bay (Ferreira *et al.*, 2008a), and the POND model for shrimp farms in Zhejiang and Guangdong provinces (Zhu, 2009). However, most of the virtual technology applications for aquaculture management in the People's Republic of China are still limited to the RTD level and few have been used in actual management practice. Nevertheless, the SPEAR project succeeded in actively involving stakeholders from farming cooperatives and local administrators in the iterative process of scenario definition, model application, and review and interpretation of outcomes, using a Driver-Pressure-State-Impact-Response (DPSIR) framework. Currently, a few influential stakeholders such as large aquaculture companies (e.g. Zhangzi Dao Co. Ltd) and high-tech aquaculture feed companies (e.g. Haid Co. Ltd) have begun to apply GIS, remote sensing, and modelling tools either solely or in collaboration with academic institutions (Zhang, Fang and Wang, 2008).

Main gaps and improvement needs according to the EAA

Integrated multi-trophic aquaculture (IMTA) firstly occurred in the People's Republic of China 1000 years ago. In "Jiatai Notes" (1201–1204) it was recorded that "In early spring fingerlings were bought and stocked into ponds, and the quantity often could be tens of thousands, most of them were bighead carp, silver carp, common carp, grass carp and black carp". In "Complete Book on Agriculture" written by Guangqi Xu (1639) it was recorded that "the optimized ratio for stocking silver carp and grass carp was 600: 200, and only the grass carp was fed with grass". The classic polyculture model is still widely being applied in the freshwater ponds all over the People's Republic of China. In mariculture, the bivalve – macroalgae – fish cage combination is also widely used, e.g. Pacific oyster, bay scallop – kelp – puffer fish cage combination culture in Sanggou Bay of Shandong, Chinese oyster – porphyra – yellow croaker fish cage combination culture in Xiangshan Gang of Zhejiang, and Pacific oyster – gracilaria – grouper fish cage combination in Zhelin Bay of Guangdong. Large-scale of macroalga or seaweeds aquaculture is also been used as a bioremediation measure for the degenerated coastal environment (Zhou *et al.*, 2006).

Because of heavy population pressure, the People's Republic of China has exploited most of the waterbodies and land that suitable for aquaculture, just as has happened to farmland for other agricultural sectors since 1980s. As such, recent research and management measures on EAA in the People's Republic of China are mostly focused on the environmental influence assessment and carrying capacity estimate (Miao and Jiang, 2007; Zhang *et al.*, 2007; Jia and Song, 2010) to the aquaculture sites that presently exist, which may be used to adjust the farming scale, reform the overall system scheming, or shut down the unqualified farm (Luo, Zhu and Bao, 2009).

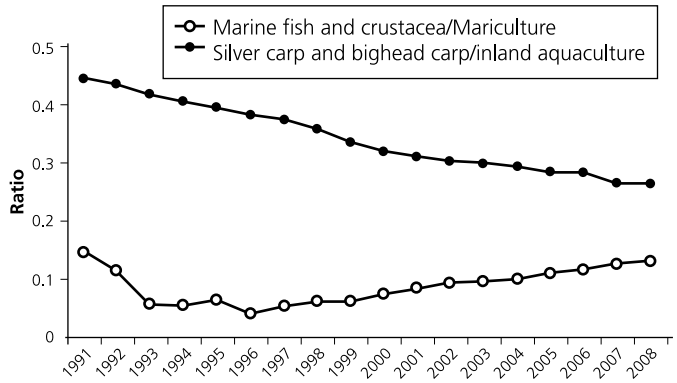
Aquaculture carrying capacity research started with the fish cage culture problems in reservoirs in the People's Republic of China in the 1980s (Li *et al.*, 1989; 1994; Xiong *et al.*, 1993). Carrying capacity research for marine systems started in early 1990s in Sanggou Bay (Fang *et al.*, 1996a, b), followed with a series of international cooperative projects on this topic, e.g. the EU project 'Carrying capacity and impact of aquaculture on the environment in Chinese bays' (1998–2001) and 'Sustainable options for people, catchment and aquatic resources – SPEAR' (2004–2007), and a lot more national projects (Lu *et al.*, 2000, 2001, 2004, 2005, 2006; Zhang, 2008) which together have greatly improved the public perspective on aquaculture sustainability and EAA.

Rapid change of aquaculture structure in the People's Republic of China

Data from the People's Republic of China Fisheries Yearbook (Fisheries Bureau, Ministry of Agriculture, PRC, 1992–2009) indicates that with intensification of farming systems and increment of species farmed in the People's Republic of China the ratio of low trophic level species production is decreasing rapidly (Figure 5). From 1999 to 2008 both productions of mariculture and inland aquaculture were increasing, meanwhile, the production ratio of marine fed fish and crustacean/mariculture increased from 6.2 percent to 12.6 percent and the production ratio of filter-feeder silver carp and bighead carp/inland aquaculture decreased from 35.6 percent to 26.4 percent.

Mariculture production in the People's Republic of China in 2008 was 13.4 MMT, of which fed species took 12.6 percent, in inland aquaculture the production of fed aquatic animals has probably reached 59 percent due to widely feeding of grass carp and tilapia in pond culture. Aquaculture as a whole in the People's Republic of China about 41 percent of aquaculture production came from fed aquatic animals in 2008. Fishmeal consumption in this industry is increasing rapidly. Such development trend indicates the weakening in net food production and increasing environmental pressures in the People's Republic of China's aquaculture industry, just as elsewhere in the world (Naylor and Burke, 2005; Dong, 2009).

FIGURE 5
The changes of the production ratio of marine fed fish and crustacean/mariculture and the production ratio of silver carp and bighead carp/inland aquaculture.



Source: Compiled from Chinese Fisheries Yearbooks, 1992 to 2009.

Identifying current and future issues and bottlenecks

Problems in water area zoning scheme and its enforcement

In May 2002, the Ministry of Agriculture of PRC published the "Trial program for water area and mud flat license system", "Specification for aquaculture water area zoning scheme" and "Outline for aquaculture water area zoning scheme", but only Guangdong, Shanxi, Fujian and Sichuan provinces had published their provincial aquaculture scheme by the end of 2007, and all of these schemes were composed based on water area zoning functions. The ultimate objective of function oriented water area zoning is to optimize the holistic functioning of the whole water system so as to protect the environment, but the current enforcement of water area zoning scheme is based on administrative regions, which aims to inspire aquaculture industry and maximize the economic benefit. The presence of such contradiction has caused the difference in carrying capacity control, aquatic environment quality and social perception on EAA among places (Luo, Zhu and Bao, 2009), e.g. although the carrying capacity for fish cage farming in Sandu Bay was investigated by the Fisheries Institute of Fujian Province during 2005 – 2007and reported that 40 percent of the cages should be removed, the cage number did not change much in the subsequent years (Zhang, 2008). A systematic reform such as setting up specific and independent water area administrative agencies might be a solution (Liu *et al.*, 2008).

Lack of effective monitoring and legislation on aquaculture effluent discharge and its consequence

At present, the intensification tendency in Chinese aquaculture is progressing rapidly, and the direct economic benefit is the main motivation. Because there is no effective monitoring mechanism on aquaculture effluent discharge and relevant legislation on effluent fee, most of the intensive aquaculture farms or areas are not equipped with effluent treatment facility, some may have such equipment but seldom in use. The lack of effective monitoring and legislation on aquaculture effluent discharge has resulted in the fact that intensive aquafarmers and companies haven't taken any responsibility for the ambient environment pollution caused by the farm effluent, which has caused the intensive farming appear with unreal and abnormal economic benefit (Dong, 2009).

Although some internationally growing intensive farming technique such as salmon cage farming and shrimp farming also have deficiencies, e.g. genetic pollution caused by fish escape, disease transmission, destroy of mangroves etc., and some may have caused serious environmental problems in somewhere (Dong, Pan and Brockmann, 2000), but could be evitable if all the needed measures are complete.

Recommendations

Any industry that aims to economic maximization but ignores environmental consequences will inevitably be unsustainable. The People's Republic of China started pond fish farming 3000 years ago, and has been honoured as the cradle of aquaculture. The ecological farming models such as rice field fish farming (ecological aquaculture), fish pond polyculture (some of them were IMTA) and mulberry fish ponds system (recycle economy) were all historically developed in the People's Republic of China, they should be highly promoted in present the People's Republic of China and improved with modern technology (Ye and Zhou., 2008; Dong, 2009).

Aquaculture carries the responsibility for the food security of the People's Republic of China's 1.6 billion people in the near future, and its development has to obey the rules of market economy. Therefore, the development of this industry cannot do without the guidance and support from the government.

For the sake of structure optimization and sustainability of aquaculture industry in the People's Republic of China, legislation and regulation on aquaculture effluent discharge management should be issued as soon as possible, and the product price must include its environmental cost. Aquaculture effluent treatment and recycle must be encouraged by the government and society.

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Environmental impact, site selection and carrying capacity estimation for small-scale aquaculture in Asia

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Abstract

Asia is the leading aquaculture region in the world, contributing to 85 percent of total world aquaculture production. Of the top ten aquaculture producing countries nine are Asian with the People's Republic of China accounting for more than 65 percent of Asian production. Aquaculture in Asia contribute more than 80 percent of an estimated 17–20 million aquaculture farmers in Asia providing livelihoods, food security and export earning power but at the same time there are growing problems with environmental impact from large numbers of small-scale producers and the difficulties in planning and management of further development. Traditional integrated aquaculture systems which are sustainable environmentally continue to play an important role for many small-scale farmers and local communities, particularly at the subsistence level. However, recently more productive and profitable aquaculture practices have developed using formulated pelleted feed and allowing intensification of production.

Small-scale producers are characterised small farm units and low productivity but in many cases, aquaculture develops in clusters of small-scale farms favouring sheltered bays, estuarine areas and coastal fringe, lakes and dams. While individually such farms create little environmental impact, the cumulative effects of large numbers of farms in "clusters" can be significant. Mitigation of these environmental impacts is difficult due to the number of individual small-scale farmers. However the effects of cumulative environmental impact can be reduced by the introduction of carrying capacity estimation using models before development, the implementation of Better Management Practices and control of feed quality and feeding strategy and management can reduce the cumulative impact.

Introduction

The purpose of paper is to highlight the continuing importance of aquaculture in Asia to provide livelihoods, food security and export earning power but at

the same time to highlight the problems with environmental impact from large numbers of small-scale producers and the difficulties in planning and management of further development.

Aquaculture in Asia has a rich history of more than 2 500 years and is recognized as the leading aquaculture region in the world, contributing to 85 percent of total world aquaculture production. FAO statistics show that there are over a hundred species of finfish cultured in the region (FAO Fishstat Plus). Of the top 10 aquaculture producing countries 9 are Asian with the People's Republic of China accounting for more than 65 percent of Asian production. In many Asian countries, the contribution to national GDP from aquaculture exceeds that from capture fisheries.

Asian aquaculture is characterised by a wide diversity of species. Production in Asia continues to grow at a fast pace due to both area expansion and production intensification. However recently, alongside this intensification of Asian aquaculture, there has been a deterioration in environmental and health conditions.

Aquaculture in Asia is dominated by small-scale farmers characterized by (De Silva and Davy, 2009):

- Small land and water areas
- Family scale operations/businesses with few small production units. For example in the People's Republic of China there are around 240 million agriculture farmers, with less than 0.1 ha
- Use of family labour
- Often based on family land (which is declining in area)
- Vulnerability to many external factors (feed price, Climate Change, market price)

Small farmers:

- Contribute more than 80 percent of an estimated 17–20 million aquaculture farmers in Asia
- Are major contributors to food production in many countries
- Are major contributors to global farmed fish supply
- Are highly innovative sector
- Are important for rural development, communities, employment, poverty reduction and environmental sustainability

Majority small-scale producers

Small-scale producers are characterised by a low-asset base, low technology and low productivity. However, they dominate the agriculture landscape throughout the developing world, and similarly play an important part in aquaculture in many countries, sometimes through livelihoods which integrate aquaculture, livestock, farm crops and other on- or off- farm activities, and sometimes through increasingly more specialization in aquaculture as a household-managed enterprise.

Small farms are characterised as largely owned and operated by households with limited access to assets such as land, water, finance and material inputs (seed, feed, etc.) and consequently, farm production volumes tend to be low. Small-scale producers in Asia face varying degrees of financial, knowledge, market access and other constraints, and therefore commonly face difficulties in raising productivity and incomes. Due to their special social, economic and environmental significance as well as the cumulative effect of impacts, environmental management measures need to give special attention to this part of the sector.

Asian aquaculture is characterised by a diversity of practices, with varying degrees of interactions with the environment. The use of trash fish as feed, and fry sourced from the wild or derived from wild-caught broodstock is still practiced widely.

Traditional aquaculture

Many of the traditional production systems in Asia have been environmentally sustainable for hundreds of years with minimal impacts to the environment (Edwards, 2009). Traditional extensive and semi-intensive forms of aquaculture, and integrated aquaculture, may be considered to represent an ecosystem approach as they tend to have less immediate impact on the wider environment than more intensive forms of culture.

Aquaculture is often integrated with agriculture with on-farm integration of aquaculture with crops and/or livestock and referred to as integrated agriculture – aquaculture systems (IAAS).

However, aquaculture may be linked with other human activity systems such as sanitation and agro-industry in peri-urban areas and fisheries. In such broader integrated systems the links between aquaculture and other activities may be direct and closely associated spatially. Examples of broader integrated systems are integrated fisheries-aquaculture systems (IFAS) which use small freshwater or marine trash/low-value fish as feed; integrated peri-urban-aquaculture systems (IPAS) using wastes of cities and industry such as wastewater (human sewage or agro-industrial effluents), waste vegetables from markets, waste food from canteens and restaurants, and factory processing wastes from the food industry, including offal from slaughterhouses and fish processing factories.

The principles of traditional aquaculture can also involve polyculture of fish with complementary spatial and feeding niches in the pond; waste or by-product reuse such as terrestrial or aquatic vegetation, livestock manure, nightsoil, brans and oil cakes, and food and drink manufacturing residues; nutrient and water reuse and multiple use between farm subsystems or enterprises; and pond for the production of high protein natural food in situ as well as an aquatic environment for fish.

BOX 1
Examples of other forms of traditional aquaculture that do not breach the carrying capacity.

Development of new integrated systems

- Asia (the People's Republic of China, the Socialist Republic of Viet Nam, the Republic of Indonesia) Rice-fish culture benefits millions of rural people; rice –fish aquaculture ecosystems have designated as a "Globally Important Agricultural Heritage System". World Fish Center (2008); FAO (2009); Lu and Li (2006); Dela Cruz *et al.* (1992)
- Asia (the People's Republic of China, the Kingdom of Thailand, the Kingdom of Cambodia, the Socialist Republic of Viet Nam, the Republic of Indonesia) Integrated aquaculture benefits millions of rural people. Edwards (2009)
- Asia (the People's Republic of China) Integrated Multi-trophic Aquaculture of fish, shellfish and seaweeds bioremediates and increases total yields up to 50 percent. Zhou *et al.* (2006)
- VAC system in the Socialist Republic of Viet Nam (VAC in Viet Namese is vuon, ao, chuong which means garden/pond/livestock pen)

Decline of traditional integrated aquaculture

Traditional integrated aquaculture systems continue to play an important role for many small-scale farmers and local communities, particularly at the subsistence level. However, recently more productive and profitable aquaculture practices have developed that require considerably increased nutrient flows than can be provided from other on-farm or local sources. Formulated pelleted feed is becoming the most significant source of nutrition for farmed fish, allowing intensification of production.

Combining intensive and semi-intensive aquaculture, some intensive pellet-fed fish farms discharge the nutrient-rich effluent into semi-intensive ponds stocked with Chinese

and Indian major carps and tilapia as a fertilizer where it is treated and converted into plankton and grazed by filter-feeding fish. Wastes from pellet-fed tilapia raised in cages are also sometimes treated and recycled in a static water pond in which the cage is floated. Tilapia fingerlings are nursed in semi-intensive culture in the pond feeding solely on natural food produced by fertilization of the pond with caged-fish wastes. Fingerlings are subsequently stocked in the cages and raised on pellets until they reached a marketable size.

The Chinese 80:20 pond fish culture system combines intensive production of one high-value species such as grass carp, crucian carp or tilapia fed with pelleted feed in polyculture with a "service species" such as the filter feeding silver carp which helps to clean the water and the carnivorous mandarin fish (*Siniperca chuatsi*) which controls wild fish and other competitors. Eighty percent of the harvest weight comes from the pellet-fed target species and the other 20 percent comes from the filter feeding service species. Such systems are widely thought to be more environmentally sustainable, however, economic incentives are driving intensification and specialization, resulting in changes to such traditional systems, with likely loss of environmental services. Another aspect of certain systems – such as rice-fish – is the implication for release of greenhouse gases (GHG). Research on rice -fish suggests that integrated systems of fish in rice fields may lead to greater release of GHGs. Further research is warranted on environmental implications of changing aquaculture systems in Asia.

Fed cage within unfed cage (the Republic of Indonesia)

Cage culture in three Indonesian reservoirs, Saguling, Cirata and Jatiluhur, of the greater Ciratum watershed, West Java, provide some other innovative approaches to resource use and management (Abery *et al.*, 2005). In all three reservoirs, cage culture of common carp, *Cyprinus carpio* L., and later of common carp and Nile tilapia, *Oreochromis niloticus* (L.), were encouraged as an alternative livelihood for persons displaced by the impoundment. A two-net culture system, locally known as 'lapis dua', in which in the inner cage (7 × 7 × 3 m) is used for common carp culture and the outer cage (7 × 7 × 5/7 m) is stocked with Nile tilapia, is practized.

There is also interest in further development of integrated mariculture systems, with some research in the People's Republic of China (ref needed) indicating multiple economic and environmental services from such systems.

Issue Identification

Devolution – decisions at the lowest level of Government

Decentralisation of government responsibilities, occurring widely across the region, is leading to delegation of some environmental planning and management decisions from central to local government authorities. This approach provides opportunities for better management, but raises considerable challenges, due to limited capacity for aquaculture planning and environmental management at local levels in many countries, and sometimes unclear or overlapping legal responsibilities and procedures and is problematic particularly in the Republic of the Philippines, the Kingdom of Thailand and the Republic of Indonesia because of weak local institutional capacities and sometimes unclear delegation of responsibilities. (Phillips *et al.*, 2004). For example, in the Republic of the Philippines the local governments are tasked to implement activities and projects related to natural resources management. However, ordinances formulated and passed by the Local Government Units (LGUs) must be in accordance with the national fishery and environmental laws. Such constraints are recognized in the Republic of the Philippines where recent "better practice" guidelines have been drafted to assist local governments in environmental management of aquaculture, and provide the basis for capacity building. Such guidelines could be made more widely available and adapted/translated to local circumstances in several countries with decentralised aquaculture management responsibilities.

Small-scale production

Small-scale producers are characterised by a low-asset base and low productivity and they dominate the agriculture landscape throughout Asia, and similarly play an important part in aquaculture in many countries, sometimes through livelihoods which integrate aquaculture, livestock, farm crops and other on- or off- farm activities, and sometimes through increasingly more specialization in aquaculture as a household-managed enterprise. Small farms are characterized as largely owned and operated by households with limited access to assets – land, water, finance and material inputs (seed, feed, etc.) and consequently, farm production volumes tend to be low. Small-scale producers face varying degrees of financial, knowledge, market access and other constraints, and therefore commonly face difficulties in raising productivity and incomes – moving up the "enterprise ladder" to become more competitive micro- and small enterprises. While individually such farms create little environmental impact, the cumulative effects of large numbers of farms in "clusters" can be significant.

Clusters of small-scale aquaculture

In many cases, aquaculture develops in clusters of small-scale farms favouring sheltered bays, estuarine areas and coastal fringe, lakes and dams (Plate 1). Success of a few farmers can often lead to rapid expansion, creating significant clusters of small farms in many areas of Asia.

Clusters of small farms often develop where there is poor control of permits, licensing or allocation of space for aquaculture development together with a lack of carrying capacity estimation. In other cases, due to fragile cage design (e.g. bamboo frames) cages are clustered in areas sheltered from strong winds and waves.

Individual small-scale farms rarely impact the environment significantly, however, clusters of farms can cumulatively cause impact within a watershed or enclosed waterbody. Improvements need to be based on collaborative management practices which add to complexity and investments needed for change.

PLATE 1
Examples of cluster farming in Asia

COURTESY OF GOOGLE EARTH

Clusters of cages in Jatiluhur Dam, Indonesia

COURTESY OF P. WHITE

Contiguous ponds in Ca Mao, Viet Nam

COURTESY OF G. S. JACINTO

Fish pens in Dagupan, Philippines

COURTESY OF G. CRISTIANSEN

Fish cages in Taal Lake, Philippines

Aceh, the Republic of Indonesia, provides an example of some successes

Fish and shrimp farming are important livelihood activities for many poor people living in the coastal areas of the Indonesian province of Aceh. Nearly 100 000 households, mainly along the north-east coast districts, depend on aquaculture for income, although productivity is very low and poverty remains endemic. Shrimp and milkfish are the major aquaculture products from Aceh, a mix that contributes to export earnings and provincial food security, along with growing volumes of tilapia, and minor species such as catfish, crabs, seabass and grouper.

A coalition of partners[1] has worked together in Aceh since 2005 to assist coastal fish and shrimp farmers and communities recover from the December 2004 earthquake and tsunami, and to build better livelihoods. Good progress has been made in physical rehabilitation of ponds and canals, introducing improvements in farming practices – so-called "Better management practices or BMPs" which have been well accepted by farmers – and rebuilding a traditional system of village farmer groups supported by innovative Aquaculture Livelihoods Service Centers (ALSCs). This approach – helping farmers to organize themselves and development of community services – run on business lines by local people for the local farming community – has worked well. In 2010, over 2 600 poor households from 82 villages joined a voluntary BMP program, supported by the four ALSCs, generating increased household incomes of US$600–800/farmer – a substantial improvement in a poor province. The approach is becoming exceedingly popular, with an estimated 6 000 farmers now showing interest and other farming communities wishing to establish ALSCs in their areas.

Environmental management improvements have been integrated into the "Better Management Practices" which are adopted at farm level, and among groups of farmers. A major driver in adoption by farmers has been the improved profitability of farming as a result, and reduced risk of disease losses. Environmental improvements are seen in reduction in chemical use, improved feed use efficiency and reduces shrimp disease occurrence. Further research is necessary on the cumulative environmental improvements in coastal areas from this cluster management approach, but they are considered to be substantial. Similar approaches are being used in the Republic of India, where farmer groups have taken increase responsibility for management of common water channels, and mangrove replanting. Further research is needed on cluster management options, and then policy and investment is required to support such local management initiatives.

Boom and bust

Some aquaculture development has been characterized by boom-and-bust development resulting in adverse environmental impacts and indicating poor governance. Over-emphasis on profit, and limited market incentives for change, or knowledge, means that farmers usually give limited consideration to environmental issues even though it is undesirable for aquaculture farms to exceed the capacity of the environment in which they are located. There are numerous cases of aquaculture severely affecting its own culture environment as well as the surrounding aquatic environment through self-pollution. Promotion of aquaculture has been successful in most countries in Asia but if a certain aquaculture venture is profitable governments have often found it difficult to control "runaway development" with often catastrophic adverse environmental impact.

Governments that are encouraging aquaculture development as a means for providing livelihoods may accept a higher level of environmental impact. Such trade-offs are common, but need much more careful consideration where natural resources are in limited supply, or competition is significant, such as in crowded lake and coastal areas, or water limited regions.

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Social, economic and environmental perspectives

Aquaculture's importance as a source of income, food, and employment for many poor people is widely recognized. Aquaculture will continue to grow, but faces a host of challenges in sustaining let alone increasing the provision of social and economic services to rural and urban populations worldwide. A number of over-arching external drivers influence the sector, such as increasing competition for ecosystem services, the use of available land and water resources for aquaculture expansion, pollution, climate change, natural disasters, HIV/AIDS epidemics, governance challenges, and local risks associated with increasing globalization and others. Internal sectoral dynamics, related to globalization drivers, are strongly influencing the sector's growth; with increasing integration of supply chains for many internationally-trade commodities now merging into domestic markets in Asia, ever higher market standards, and competitive forces driving buyers to most efficient and reliable producing countries.

Within this generally dynamic picture of growth and change, small-scale aquaculture farmers, in common with agriculture farmers, face significant challenges. Limitations related to infrastructure, producer capacity, access to finance, public sector servicing capacity and other factors often create a cycle in which low productivity depresses income and thus a "vicious cycle" of deepening problems. They are also among the most vulnerable to external drivers such as climate change, market demands and other factors which are largely out of their control. Coordinated engagement by private and public stakeholders, including the business sector, can help address such dynamics. Approaches to improve environmental management need to take account of these different aspects.

General considerations

Production aspects

Brackish water and marine fish and shrimp pond culture

Penaeid shrimps are widely cultured in coastal ponds. Other commodities that are cultured include brine shrimp, milkfish, mullets, mud crabs, and seabass. Ponds cover a wide range of coastal areas from backishwater estuarine areas to coastal mud flats. Along with this large spatial distribution, there are a variety of culture intensities of production (from extensive to super intensive) practiced. Semi-intensive and intensive shrimp culture area has developed rapidly, but faces a number of issues such as intake and effluent output to the same water source leading to self-pollution, the sharing the same water source with other farms up or down stream and lack of zoning.

Other than where large areas of coastal wetland ecosystems are removed for ponds environmental impact is low from extensive or traditional systems which operate at low stocking density and without any supplemental feed except some fertilization. Impacts afre also lowfrom semi-intensive systems, where a small amount of supplemental feed is given for a part of the culture period. However, higher impact is experienced from intensive systems, where the majority of the nutrient supply comes from compounded feed and there is a much greater requirement for management.

Waste water from shrimp ponds is often discharged directly to estuaries with impacts on other shrimp farms and the local environment. However much of the nutrients from feed and fertiliser remain in the pond and contribute to primary production and supplemental feed for the shrimp and fish. Nutrients are released during exchange of water in the pond and after harvest when pond sludge is removed, the latter being a significant component of waste load.

Nutrient release to the environment can be reduced by the use of sedimentation ponds for the effluent water.

TABLE 2
Key pollutants from intensive and semi-intensive shrimp systems the Socialist Republic of Viet Nam.

Environmental effluent budget	Intensive (kg/ha/year)	Semi-intensive (kg/ha/year)
Dissolved nutrients		
Nitrogen load	176	54
Phosphorous load	12	4
Particulate nutrients		
Nitrogen load	156	48
Phosphorous load	100	31
Organic waste	5 422	1 662

Source: EASRD (2006).

Freshwater fish pond culture

The majority of Asian fish production is undertaken in freshwater ponds for carp production. Similar to brackish and marine ponds, nutrients generally remain in the pond. Sediment accumulating in the fish ponds is usually used to increase the height of the pond walls or as fertilizer for orchards or agriculture.

Le (2005) calculated that nutrient released from intensive culture of *Pangasius* catfish ponds was estimated about 23.2 g of nitrogen and 8.66 g of phosphorus per kilogram catfish production. Nevertheless, research on such systems in the Mekong Delta of the Socialist Republic of Viet Nam suggests that they make only a small contribution to net loadings of nutrients to the delta and coastal waters (De Silva and Davy, 2009).

The location of freshwater farm plays an important role in fish pond management and practices. Farms are typically situated along rivers, river branches, water canal, and irrigation canals which have favourable condition with regard to available water resources. However, water quality may contain toxic residues, pesticides or organic matter which is discharged from agriculture, industry sources or residence areas without treatment. Floods may also be threat the fish ponds in the rainy or flood season.

Fish farms which originate in rice fields may share the water resource with agriculture. These farms normally locate far from residence areas thereby reducing the negative impact of human activities and conflict among communities. However, activities in the paddy fields, such as the application of pesticides, may negatively affect ponds. Water shortages in ponds may occur when paddy fields start to be irrigated. Farm located in residence areas may receive water waste from human, animal raise activities. Water source is usually from rain or groundwater. These farms are hard to manage because of limited water source and security issues.

Cage-pen aquaculture

Culture of fresh and brackish water finfish (milkfish, tilapia, flounders, grouper, carp, Asian sea bass) is widely practiced though out Asia. A limited number of marine fish species such as, rabbit fish (*Siganus canaliculatus*), Asian sea bass (*Lates calcarifer*), red snapper (*Lutjanus argentimaculatus*), grouper (*Epinephalus spp.*) are cultured in tropical coastal areas. In cage and pen culture, water passes through the nets freely and the distribution of the nutrients is highly influenced by the hydrodynamics of the site location. All excess nutrients are released to the environment increasing the dissolved nutrient concentration in the waterbody and enriching the sediment beneath the cages. If the environment is not able to assimilate these nutrients quickly enough they will tend to accumulate causing eutrophication and changes to benthic biodiversity. In many parts of Asia, cages are typically located in nearshore more

sheltered coastal areas. This is for traditional reasons of security and ownership and because most cages are small-scale locally made operations, with limited capacity to withstand more open environments. To date, there has been little use of offshore cages, although interest is increasing and the number of more offshore located farms is slowly increasing, particularly in the People's Republic of China and recently in the Republic of Indonesia and Malaysia.

Raft culture

Mussels and oysters and seaweeds are cultured using rafts or longlines. However, culture of these commodities is considered as environment friendly due to their nutrient assimilating capacity. Despite their role in assimilating nutrients, molluscs also cause localized biodeposition of pseudofaeces, which have some impacts similar to those of wastes deposited of marine cage culture. Though mussels or oysters act as a bio-filter, organic pollution from large-scale mussel or oyster culture in form of pseudofaeces cannot be neglected. For example, an individual mussel produces 5.7 mg organic matter per day (Dankers and Zuidema, 1995). A typical oyster rack with 420 000 oysters can generate 16 tonnes of faecal and pseudofaecal material during a nine month culture period. Deposited organic matter that originated from mollusc farms stimulates microbial activity, thus increase BOD, sulphate reduction and denitrification (Nunes and Parsons, 1998).

Longlines

In the tropics, seaweed is a rapidly growing aquaculture industry and currently occupying a large proportion of world aquaculture production in wet weight basis. Commonly cultured species are *Eucheuma sp* (the Republic of Indonesia, the Republic of the Philippines), *Kappaphycus sp*. (the Republic of Indonesia), *Gracilaria sp* (the Republic of Indonesia, the Republic of the Philippines, the Republic of Fiji), *Porphyra sp*, *Nori sp* (Japan), *Enteromorpha sp* (Japan, United States of America), *Caulerpa sp, Codium sp, Hypnea sp, Soliera sp, and Acanthophora sp* (the Republic of Fiji).

Nutrient balance

Most aquaculture production systems are based on nutrients imported from outside the system, although some are primarily dependent on relatively local sources (e.g. manure). Others use regional resources (such as food processing wastes, fresh trash fish) while yet others use global sources (commodity feedstuffs and fertilizers). Traditional integrated agriculture aquaculture involves relatively little waste discharge to the wider environment of the waterbody or watershed. Internal or relatively local recycling serves the dual purpose of enhanced production and waste assimilation. It has been suggested that such systems might offer a model for ecologically sustainable aquaculture but many depend on the import of feed for livestock, whose wastes in turn serve as the inputs to aquaculture. Furthermore there is a general tendency to intensify these systems.

Wastewater-fed aquaculture actually serves as a waste treatment system as it uses domestic wastewater as a source of fertilizer and feed. These systems act as net extractors of nutrients from the environment, so effluents are "cleaner" than the influent. However, waste-water fed systems are in decline. Although there are guidelines to safeguard public health (need reference), they are largely being replaced by modern wastewater treatment facilities. The quality and productivity of the fish is compromised by toxic industrial effluents and they are typically located in peri-urban areas where the value of land is rising rapidly due to urban development.

Most modern fish culture involves more intensive input of nutrients in the form of feed, with only a small proportion of the nutrients actually being converted into the target product. The rest accumulates in the system and is discharged in waste water or is removed as pond sludge and applied to pond dykes where it may fertilize fruit trees,

or to waste ground or agricultural land. Effluent discharge to canals, rivers or lakes may cause eutrophication, an undesirable ecosystem change. In other cases, depending on dilution rates, effluents may be a beneficial addition of nutrients which boosts natural or agricultural productivity.

Environmental aspects

Not all the nutrients given as feed are assimilated by the fish and other aquatic animal products as production. A large proportion is excreted either as dissolved nutrients that increase their concentration in the water column or as faeces that settle to the sediment. The level of nutrient release is greatly influenced by feed quality, feeding strategy, over-feeding and type of feed (pellet, trash fish, home-made feeds). The exceptions are most molluscs, which are net removers of nutrients and organic matter from the environment, although even then molluscs farms can have significant influence on ecosystems through alteration of nutrient cycles.

Factors affecting release of nutrients and organic matter include poor utilization of feed resulting in poor Food Conversion Rate (FCR), the quality of dry feed or trash fish and the feeding strategy. FCRs can vary between 1.2:1 for salmon to 2.8:1 (or higher) for milkfish (commercial pellets) depending on feed quality and feeding strategy. Feed can contribute up to 60 percent of the total production outlay for commercial aquaculture. Aquacultural feed management strategies control how farmers feed their fish and have a considerable influence upon the economic and environmental sustainability of their enterprises (Cho and Bureau, 1998). Feed management regulates ration size, the spatial and temporal dispersal of feed, feed delivery rate and the frequency and duration of feeding events (e.g. Talbot Corneillie and Korsøen 1999). In addition to influencing key performance indicators such as growth rate or food conversion rate, each of these components can also have a profound effect upon environmental impact.

Feed formulation

A primary concern amongst aquaculturists is to deliver feeds that meet the nutritional requirements of the fish at ration sizes that optimize both growth and FCR. However, the exact energy and nutritional requirements are often not fully known leading to nutritional imbalances and causing reduced fish performance. Fish feed producers have responded to the need for simplicity in daily farm operations by producing generic formulations for species such as milkfish but that are grown in very different culture conditions (ponds and cages) by offering feed products recommended for culture systems. However, fishes grown in cages and ponds have different nutritional requirements. It is therefore important to understand the impacts on cost efficiency, animal welfare and environmental impacts of using species-specific feeds and feeding protocols and to use this information to design better, more system-specific feeds.

Feed quality

The quality of dry compounded feeds is influenced by the digestibility of the ingredients, the suitability of the formulation to individual cultured species and season, the stability of the pellets in water, the storage and handling of the feed and whether the feed is extruded or pelleted.

Feed type

There is generally a lack of feeds formulated for specific species, for specific culture systems and for different seasons. In addition many small-scale farmers produce farm-made feeds. Farm-made feed are generally less stable in water and have poorer FCRs than manufactured feed, leading to increased pollution. There are particular concerns about pollution from cage effluents, deterioration of water quality and fish disease

outbreaks. Ammonia, nitrates, and organic matter released in faecal wastes can be assimilated rapidly where high water temperatures prevail. Feeding trash or low value fish also results in environmental impacts. The quality of wet feed (Low-value/Trash-fish) is influenced by quality and storage, whether the trash fish is fed whole or chopped or minced, as this influences the leaching of nutrients into the environment before being eaten. The age (days after capture) and storage conditions of the trash fish influences bacterial levels in the material and the addition of bacteria to the culture water.

Food conversion rate

Feed Conversion Rates (FCR) are determined by many factors including appetite and palatability (and thus how much food is ingested), by digestibility, nutritional needs and fish metabolism. Dietary ingredients, feed manufacture feeding regime, species, fish size, water temperatures and oxygen levels also influence FCR. The recorded feed conversion rates for farmed fish may vary widely from farm to farm and with production cycle. Farmers can improve FCR by feeding the appropriate quantity of feed amount, and by considering when, for how long and how often to feed.

Feeding strategy and management

The greatest influence on the amount of excess nutrients entering the environment is through poor feeding strategy by the farmer, resulting in under- or over-feeding.

Under-feeding has detrimental effects on production efficiency (Bureau, Hua and Cho, 2006) while over-feeding typically increases feed wastage (Thorpe and Cho, 1995), leading to poor feed conversion ratios (Talbot, Corneillie and Korsøen., 1999) and excess feed wastes that contribute to environmental degradation in cage culture (Cho and Bureau, 1998). Appetite and feed consumption rates of fish vary within and between days and also between seasons (Noble *et al.*, 2007) and commercial fish farmers must address each of these factors when designing economically and environmentally sustainable feed management strategies.

Aquacultural feed management strategies determine how a farmer feeds their fish. In addition to influencing key performance indicators such as weight gain or feeding efficiency, each of these components can also have a profound effect upon fish behaviour and welfare. A primary concern amongst aquaculturists is to deliver a ration size that optimizes both growth and feeding efficiency, and many aquaculturists still rely upon experience or feed tables to establish the daily ration sizes for fish. Although these recommended rations are based upon extensive research into fish nutrition, they assume fish will consume food whenever it is offered, irrespective of time of day or feed regime or health status.

An important opportunity to improve governance and management of the aquaculture sector and thus increase the social and economic benefits to small-scale producers lies in promoting and developing collective action in the form of farmer organizations or "clusters". Clustering of smaller producers can create economies of scale and volumes that attract business, sellers of fish feed and fry, and buyers of aquaculture products.

Farmer cooperatives have been widely promoted in agriculture but there is little well documented information on cluster farming by commercially-oriented small-scale aquaculture producers. Recent experiences in the field show that promotion of cluster farming in aquaculture and managing these clusters with technical improvement, such as through application of better management practices (BMPs), can yield benefits. Such approaches can be successful tools for improving aquaculture governance and management of small-scale producers to work together, improve production, develop sufficient economies of scale and enhance knowledge that allows participation in modern market chains and thus reduce vulnerability. Such governance and management approaches can lead to improved economic performance of the aquaculture sector, better farm incomes and improve resilience of farm production systems and households.

Planning

Strategic planning

Strategic planning is widely recommended as a way to address the cumulative environmental effects of large numbers of small-scale aquaculture developments which characterize the bulk of aquaculture worldwide (e.g. GESAMP, 2001). However very few countries require or have implemented Strategic Environmental Assessment for aquaculture development.

Strategic Environmental Assessment (SEA)

Strategic Environmental Assessment offers a comprehensive approach to identifying likely sectoral impacts, and establishing environmental objectives, standards, limits and so on for the industry. It is also a good basis for developing aquaculture development and management plans or integrated coastal zone management plans (ICZM). Strategic environmental assessment (World Bank, 2008) is a new concept to the region. As of 2005, only the People's Republic of China, Hong Kong Special Administrative Region, Japan, the Republic of Korea and the Socialist Republic of Viet Nam have legal requirements, to a certain extent, for SEA at national or local levels, or for aquaculture plans. SEA is being implemented in South Australia, and New Zealand.

Australia provides one example where environmental assessment is conducted on proposed aquaculture zones in coastal areas, which can be considered a form of SEA. The Republic of India has also conducted an environmental assessment of the shrimp-farming sector. The People's Republic of China is increasing attention on environmental assessment of "special programmes" that can include aquaculture development plans. While many countries are enshrining the possibility of applying SEA to the aquaculture sector there has been limited application to date.

It is important to encourage and apply strategic assessment for large numbers of small projects. Government investment will likely be necessary for the conduct of such area based SEA initiatives, as is common in Australia, for example.

Zoning

Many countries in Asia do not have formal planning relating specifically to aquaculture, but do have land and water use zones which may restrict aquaculture activity. Zones may be either positive (i.e. aquaculture development zones or parks) or negative (i.e. aquaculture is excluded or highly restricted). Positive zoning is relatively unusual, though well established in some countries such as the People's Republic of China, Japan, Republic of Korea. Aquaculture "Master Plans" have been developed in the Socialist Republic of Viet Nam and include some provisions for zoning. In Malaysia informal assessments have been undertaken for zoning initiatives, such as the Sabah Master Plan for aquaculture development. In the Republic of the Philippines the new National Code of Practice serves as the basis for local framework. Planning for aquaculture is also relatively highly developed in the People's Republic of China and Japan.

Aquaculture parks

Aquaculture "parks" have been promoted in some Asian countries. This represents a very positive approach to aquaculture development planning and management but needs to be handled carefully with carrying capacity estimation and restriction of licenses otherwise the cumulative impact could severe in enclosed and semi-enclose waterbodies.

Environmental Impact Assessment (EIA)

EIA legal requirements are commonly focussed on high value, intensive farming, and particularly shrimp and marine cage farming Asia. Most legislation is oriented

towards farms that cover larger areas, and that have a high potential environmental impact. Small-scale and inland aquaculture systems are less subject to EIA legislation/regulations. Seaweed and mollusc culture is rarely mentioned in EIA legislation or guidelines. To date EIA has only been applied consistently to some large-scale shrimp farming projects in South East Asia and to marine finfish farming in Australia. It is difficult to apply it to large numbers of small-scale fish farm developments. In Asia, the requirements for EIA and monitoring are ambitious relative to the capacity to deliver. Capacity is weak in several dimensions: general skills (although country papers do not generally identify this as a key constraint); access to essential assessment and monitoring techniques; financial and institutional support; and enforcement.

Carrying capacity estimation

A key issue for sustainability of aquaculture is extent of nutrient discharge or other wastes to the receiving waterbody, which may lead to a deterioration in ecosystem structure (biodiversity) and the supply of ecosystem services (food, clean water, waste assimilation, etc.). To address this requires an understanding and assessment of assimilative (environmental) capacity. Environmental capacity is dependent on society's wishes and needs. If it can be estimated, then strategic precautionary limits might be placed on aquaculture and other activities to ensure that standards are not breached.

Carrying capacity in Asia is often seasonal (PHILMINAQ, 2004). The nutrient release from watershed after the first heavy rains of the rainy season release high levels of nutrients into the waterbody that are in addition to the input from fed aquaculture and other inputs. This can lead to lowering of the aquaculture production carrying capacity and if this is not taken into consideration greatly increases the risk of algal bloom and low oxygen levels that can result in fish kills.

BOX 2
Carrying capacity estimation in Japan.

Japan, with its long established intensive marine farming industry, has studied environmental capacity issues for some time. The approach has been to define environmental capacity in terms of the *maximum rate of assimilation*. Benthic oxygen uptake is taken as an indicator of the rate of mineralization and benthic ecosystem activity. This peaks at a certain organic matter loading, beyond which function is clearly impaired. This is taken to correspond to environmental capacity and the total organic matter loading from farms must not be allowed to exceed this amount.

This is an example of managing the environment to maximize an environmental service (i.e. organic matter mineralization) in this case a service to the aquaculture industry itself. This contrasts with the approach in many other countries, where environmental capacity is usually defined in terms of the organic matter or nutrient loading which can be accommodated without breaching the particular water quality standard agreed for that waterbody usually through reference to historic water quality, national standards, or as agreed with other users. In other words the focus is not just on ensuring sustainable aquaculture, but on maintaining water quality for a variety of reasons. Japan has also developed indices of site suitability based on embayment degreeand specific characteristics (water/sediment/fauna) which to some degree serve as indicators of environmental capacity.

Many countries, including the Republic of Indonesia, Japan, the Republic of the Philippines and the Socialist Republic of Viet Nam, are now developing environmental capacity models for a range of waterbodies,. In Japan these assessments are used to inform "Aquaculture Ground Improvement Plans".

Models

A variety of models are used in Asia for aquaculture planning and are based upon:

- Modelling environmental impact
- Modelling carrying capacity

Carrying capacity models

Carrying capacity models need to be more widely available, tested and suitable models promoted. Calculations in the EIA to assess carrying capacity of the waterbody and the farms should take into account the other farms in the waterbody and not only individual farm projects. A useful summary of existing carrying capacity models for aquaculture is provided in McKinnon (2007). A number of models to calculate carrying capacity are currently in use (Table 1). Two of these are of particular relevance to the Asia Pacific region.

- CADS_TOOL (Cage Aquaculture Decision Support Tool), developed under ACIAR project FIS/2003/027, currently includes 5 modules.
- The MOM (Modelling, On-growing and Monitoring) model developed by Stigebrandt *et al.* (2004) for salmon has been modified to apply to grouper, barramundi and rabbitfish.
- The model of Hanafi *et al.* (2006), based on an oxygen budget for Pegametan Bay, Bali, and applied to grouper aquaculture
- The model of Tookwinas *et al.* (2004), another oxygen-based model developed in the Kingdom of Thailand
- The model of Pulatsü (2003) for freshwaters, based on a phosphorus budget.
- The box model of Legovic *et al.* (2003) for fresh, brackish and marine waters based on nutrient levels that trigger algal blooms

TABLE 1
Summary of status of carrying capacity models used in modelling aquaculture in the Tropics

Model	Country	Environment	Species	Culture system	Basis
MOM/simplified model	Norway, Indonesia Vietnam	Marine	Salmon, now simplified being tested on tropical systems (seabass, grouper, rabbit fish)	cages	Carrying Capacity Multifactorial Water quality
TROPOMOD	The Philippines	Marine and Freshwater	Validated for milkfish – marine and Tilapia – freshwater	Cages and pens	Deposition of organic material
Siri Tookwinas (DOF/ SEAFDEC)	Thailand	Marine	Shrimp Grouper	Ponds	Carrying capacity NH3-N
Hanafi	Indonesia	Marine	Grouper		Carrying capacity O2 budget
Pulatsu	Turkey	Freshwater			Phosphorus
Cirata Dam. Dr Sonny Koeshendrajana, Centre for Marine and Fisheries Socio-Economic Research Agency for Marine and Fisheries Research and Development	Indonesia,	Freshwater	Common carp and tilapia	cage culture	Phosphorus
Linear regression model (The Philippines)	Philippines	Marine and Brackish	Milkfish	Ponds and cages	Carrying Capacity based on water quality
GESAMP model					Consolidation of Models based on phytoplankton and feed
Legovic model	The Philippines	Fresh, brackish and Marine	Milkfish and Tilapia	Cages and pens	

Models to predict aquaculture impact

TROPOMOD, developed under PHILMINAQ, is an extension of DEPOMOD and MERAMOD, originally applied to cage finfish mariculture in Scotland and in the Mediterranean respectively, has been developed to apply specifically to milkfish farming in the Republic of the Philippines, but has application to other tropical species. In freshwaters, it has been successfully applied to tilapia. This model is a sediment deposition model and has the goal of minimizing deterioration of sediment quality.

Management

Environmental Management Plans

EIA legislation for aquaculture widely includes reference to Environmental Monitoring Programs (EMPs) that include environmental monitoring. Monitoring is of fundamental importance to effective environmental management of aquaculture and is strongly linked with EIA as a process to monitor and evaluate the impact. Often there is limited implementation of monitoring requirements as developed in EIA environmental management plans, and limited analysis, reporting and feedback of farm level. In addition, it rarely addresses the wider environmental monitoring of a number of farms located in the same waterbody. However, examples can be found in the extensive environmental monitoring networks for fisheries in the People's Republic of China and the developing systems in the Socialist Republic of Viet Nam, both of which involve substantial investment.

Monitoring

Environmental monitoring is a significant activity in most countries, typically undertaken by government authorities. Where fish farming is larger scale, companies usually undertake their own monitoring – either as required by government (sometimes directly arising from EIA and associated EMP), or for their own management information. Most countries also have national water quality monitoring systems which are not specifically related to aquaculture but serve to alert public authorities of any problems which may arise. In some countries third parties may be involved – or partnerships of interest (e.g. the Republic of the Philippines) to ensure neutrality and representation of stakeholder interests.

In Japan, fishery cooperative associations are required to undertake monitoring and reporting for the farms in their area, assisted in some cases by prefectural fishery stations. In New Zealand and Australia monitoring programmes may relate directly to marine plans or aquaculture development plans, and be tailored to particular issues and zones as required. In the People's Republic of China there is now a major sector related monitoring programme – the Fishery Environmental Monitoring network – covering 21 million hectares, with a major centre in Beijing. This covers inland and nearshore coastal waters with both disease and environmental components. A similar system is being developed in the Socialist Republic of Viet Nam.

Programmatic monitoring

In the Republic of the Philippines there is provision for Programmatic Environmental Performance Report and Management Plan – but this has not yet been implemented in coastal and lake based aquaculture.

Indicators and standards

Environmental quality standards

The existence and use of standards as part of the environmental management of aquaculture, and to inform permitting procedures, enforcement, EIA and other procedures is highly variable. In many countries water quality standards are well developed, and in Europe these are now being applied in relation to particular

waterbodies. In developing countries water quality standards have sometimes been copied from developed countries and may not reflect local conditions or needs.

Water quality standards

The Association of South East Asian Nations (ASEAN) has started the process of standardizing water quality standards within the Southeast Asian region. In many countries standards are applied in relation to the effluent quality itself. In the Republic of India and the Socialist Republic of Viet Nam for example there are now national standards for wastewater from aquaculture. These are of two types – for discharge to coastal marine waters, and for discharge to creeks/estuaries. While these serve as a starting point for limiting discharges, they do not take account of the capacity or characteristics of a particular waterbody.

Acceptable water quality standards

The water used for aquaculture should be suitable for the production of food which is safe for human consumption. Farms should not be sited where there is a risk of contamination of the water in which animals are reared by chemical and biological hazards. If wastewater is used, WHO guidelines for the use of wastewater in aquaculture should be followed (WHO, 2006). Farms should maintain water quality within the relevant national water quality standards. Standards for freshwater are commonly set and used by national governments and their agencies, throughout the world. In many cases levels are already set at what might be termed precautionary levels. Some of these apply specifically to aquaculture although implementation remains limited. The standards used by government usually relate, very loosely, to nutrient levels which may cause algal blooms and de-oxygenation, or compromise drinking water quality. These issues however need to be examined in relation to a waterbody or system, and the needs and aspirations of people who depend on it.

Governance measures

Codes of Conduct (COC) and Good Aquaculture Practice (GAP)

Codes of Conduct (CoC) or Good Aquaculture Practices (GAP) have been initiated by government, private sector and NGOs and are increasing in number; some linked to certification schemes and market access requirements. The increasing proliferation of CoCs, BMPs and certification schemes appears to be in response to market demand, particularly with exported products, and food safety concerns associated with aquaculture products. The cost to comply with these schemes can be borne by the larger companies especially if they are exporting their products. However the costs are prohibitive for small individual producers and so the is effort to try and incorporate clusters of small-scale producers into these schemes.

The major shrimp farming companies have been very proactive, recognizing early on the need to strengthen their environmental credentials, minimize disease, and ensure that the industry developed steadily and sustainably. Some are now working with WWF toward eco-certification under the guidance of the International Principles for Responsible Shrimp Farming (FAO/NACA/UNEP/WB/WWF, 2006).

In the Republic of the Philippines a national and legally binding Code of Practice for aquaculture has been developed. This goes beyond many other codes in so far as it also defines permitting and regulatory procedures, as well as farm operation requirements and standards. As such it amounts to a complete management framework. The code includes for example a requirement for local government and producers to identify suitable zones and sites; a requirement for an environmental impact statement for new construction; and specific provisions for the spacing of cages and the need to establish carrying capacity. In addition to these planning related provisions, the code includes standard good practice provisions relating for example to organic waste, introductions, medicines etc.

Much stronger emphasis is also needed on improving environmental management among the small-scale farming sector, through simple regulatory procedures and voluntary measures that support improved environmental management, assisted by improvements in the financial and technical services that will support the transition to better management. Costs associated with such management also need to be carefully considered as it is unlikely the management costs can and should be absorbed by the small-scale producer.

Cluster management[1]

Cluster management in simple terms can be defined as collective planning, decision-making and implementation of crop activities by a group of farmers in a cluster (defined geographical area for example sharing common water source) through a participatory approach in order to address the common risk factors and accomplish a common goal (e.g. maximise returns, reduce disease risks, increase market access, procure quality seed). Promotion of BMP adoption through a cluster management approach reaches more farmers. Cluster management brings several advantages to individual farmer members which otherwise is not possible. Because of the economies of scale which a cluster can achieve, forward and backward integration of culture operation with processors and hatcheries, respectively, is possible. A cluster approach increases the bargaining power and helps farmers to source quality inputs.

Certification, which is cost prohibitive for individual farmers, can be accomplished through cluster certification. A cluster approach makes it easy to access credit and insurance compared to an individual farmer. The principle of sharing costs in a cluster approach ensures that common facilities such as feeder canal, roads and other infrastructure can be developed and maintained properly. Peer pressure prevents fellow farmers from resorting to irresponsible culture practices such as the use of banned antibiotics, release of water from disease affected ponds.

The key to cluster management is continuous and regular communication within and among groups. This can be achieved through regular meetings and or through the use of modern communication tools, which contrary to popular belief, rural farmers acquire the skills to use easily. In the Republic of India and the Kingdom of Thailand, new approaches are being explored to certify clusters or farmer groups, as an alternative to individual farm certification, offering perhaps a new market incentive for organization of clusters and improving collective management. Such systems commonly require improvements in internal management, particularly internal control systems involving record keeping, to be acceptable. As in the case of cluster management generally, investment is needed in skills development and in some case facilities to facilitate adoption of certification in clusters.

Better Management Practices

BMP projects, in the Republic of India, the Republic of Indonesia, the Kingdom of Thailand and the Socialist Republic of Viet Nam provide good examples of translating the principles of responsible aquaculture into specific BMPs adapted to local farming conditions and ensuring their implementation by relevant stakeholders, with consequent gains in production, quality improvements and market accessibility.

They also show evidence of the advantages of small-scale farmers being organized (farmer groups/societies), sharing resources, empowering the stakeholders, helping each other and adopting BMPs. The implementation of the better management practices has provided benefits to the farmers, environment and society.

BMPs need to be grounded in valid scientific justification, rather than perceptions and or superficial experiences. Thus there is a need for R&D to validate key BMPs, and to quantitatively assess their impact on farm production and economics. Equally, there

[1] library.enaca.org/AquacultureAsia/Articles/jan-march.../3-bmps.pdf

is a need to develop implementation mechanisms to permit large-scale scaling up of BMPs to create impacts among large numbers of small-scale farmers. Implementation mechanisms should also, far as possible, be supported by and built on systems already in place in the relevant country i.e. the cultural contexts prevalent in each country have to be taken into consideration.

Ways forward

How can small-scale farmers best benefit from the continued rapid growth of the aquaculture sector, and demand being created for food fish as populations grow and capture fisheries production stagnates? What synergies between small-scale producers and larger enterprises can best benefit poor rural and urban households in terms of employment, food supply and better livelihoods? How can the required technical and financial services be provided to small-scale farmers to improve and remain competitive in modern markets?

Some new approaches are emerging. Investing in better organization of smaller producers and improved technical and financial services can pay dividends. Small business-oriented services are emerging in several rural areas in Asia, leading to significant improvements in profitability of small aquaculture enterprises. An important opportunity to improve governance and management of the aquaculture sector and thus increase the social and economic benefits to small-scale producers lies in promoting and developing collective action in the form of farmer organizations or "clusters". While not applying to all circumstances, there are significant opportunities to improve environmental management through such organization. Clustering of smaller producers can create economies of scale and volumes that attract business, sellers of fish feed and fry, buyers of aquaculture products, and build social capital.

Farmer cooperatives have been widely promoted mechanisms in agriculture, but there is little well documented information on cluster farming by commercially-oriented small-scale aquaculture producers. Recent experiences in the field show that promotion of cluster farming in aquaculture and managing these clusters with technical improvement, such as through application of Better Management Practices (BMPs), can yield benefits. Such approaches can be successful tools for improving aquaculture governance and management of small-scale producers to work together, improve production, develop sufficient economies of scale and enhance knowledge that allows participation in modern market chains and thus reduce vulnerability. Such governance and management approaches can lead to improved economic performance of the aquaculture sector, better farm incomes and improve resilience of farm production systems and households.

While more studies are needed, economic analysis also suggests that investments in services can yield substantial social and economic benefits – investments of the MPEDA/NACA project in the Republic of India for the period of 2004–2006 showed that for each Indian Rupee invested in the technical assistance program, a profit of nearly 16 Rupees was provided for coastal shrimp farmers (Umesh *et al.*, 2009). At the same time, the establishment, maintenance and enforcement of appropriate legal, regulatory and administrative frameworks in developing countries (producers of majority of aquaculture products) are key requirements towards responsible and sustainable aquaculture sector. These frameworks should cover all aspects of aquaculture and its value chain and provide economic incentives that encourage best practices, thus, prompting and assisting farmers to elaborate, support and enforce self-regulating management codes and promote sustainability-conducive production systems.

In an increasingly globalised and market-oriented economy, we also need to find ways in which the larger private sector players can contribute more effectively – business solutions that work for small-scale farmers, organizations and small-scale farm services are required.

Commonly, small projects investing in farmer organizations and improved practices can work well, but sustaining these beyond the subsidy of the project requires more business-oriented approaches and solutions. The challenge today is to help build the capacity of smallholders and their organizations so that they can deliver what the market requires, and in turn encourage businesses to adapt their models to be inclusive and supportive of small-scale producers (Vorley, Lundy and MacGregor, 2008). It also means bringing together different players and skills along the value chain for sustainable enterprise development. Within the context of better management of clusters, there is also a need to explore ways to integrate environmental management tools – planning and monitoring tools that can work for farmers and farmer groups.

General recommendations

There should be more widespread testing and adoption of planning tools within environmental carrying capacity. Pilot activities can be successful, but adoption at scale remains a considerable challenge. Government ownership, policy and investment is necessary to adopt at a large-scale, leading to more widespread environmental improvements.

The concept of BMPs should be expanded with further work on responsible feeding practices and handling of wastes.

Farm management options to reduce impact on the environment should be promoted such as the use of cage rotation, fallowing, effluent sedimentation ponds, etc.

When planning and siting of large clusters of small-scale aquaculture, there should be Programmatic EIAs or Environmental Statements undertaken with production carrying capacity modelling for the cluster so that the planned development is environmentally sustainable.

There should be systematic and regular monitoring of water and sediment quality around large clusters of small-scale farms. This could be undertaken as co-monitoring by the cluster organization or by the local government Agency.

There should be promotion of open sea farming for larger aquaculture enterprises in Asia to have high production farms located in deeper water and with stronger water currents.

Polyculture of appropriate species (e.g. Muilti-Trophic Aquaculture, or MTA) may reduce waste loadings. Incentives for integrated farming need to be explored and provided. Research is also necessary on the social, economic and environmental services from integrated farming systems, the influence of change on such services, and ways in which benefits can be optimized.

Research on clusters approaches, and environmental management and policy tools necessary to support a more organized and better managed small-scale farming sector where appropriate.

There should be further development and promotion of CoCs, BMPs with particular emphasis on reducing environmental impact.

The co-management of clusters should be encouraged with 30 to 50 contiguous farms with a defined border with the cluster of farms co-managed interms of inputs (joint feed and seed purchasing), use of the area (carrying capacity), outputs (planned harvesting and joint marketing) with joint environmental monitoring, feed quality managerment and biosecurity management.

The clusters should be encouraged to link with other clusters to form a network of all the clusters in a given waterbody into a sort of producers organization. Service support (net makers, cage makers, harvesters) for the clusters or network of clusters should also be organized into associations. Local or provincial governments should be persuaded to put the basic infrastructure (improved roads, jetties, feed storage areas, harvesting areas with ice machine, etc).

National aquaculture agencies should be encouraged to provide extension and training to the clusters or network of clusters.

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Carrying capacity and site selection tools for use in the implementation of an ecosystem-based approach to aquaculture in Canada: a case study

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Abstract

Coastal British Columbia, Canada is employed in a *case study* of aquaculture carrying capacity issues – illustrating how this jurisdiction currently manages aquaculture site selection and operations, and how ongoing changes to its overarching policy and regulatory processes relate to the development of an ecosystem-based approach to aquaculture in this jurisdiction. Environmentally, carrying capacity issues are addressed using a combination of GIS-based resource mapping and spatial separation guidelines, DEPOMOD simulations of organic waste dispersion/accumulation, and performance-based monitoring using physical-chemical surrogates of biological response to ecosystem stress. The environmental tools for carrying capacity and site selection are not applied equally to all aquaculture sectors and deficiencies in the approach are recognized as significant gaps to forming a comprehensive, and defensible ecosystem approach to aquaculture (EAA). Socially, British Columbia aquaculture competes with a variety of coastal stakeholders, and the issues and interactions among these stakeholders are considered and integrated into the management (siting, carrying capacity, operating) framework of this social-ecological system. New initiatives to assess social-ecological performance, in the form of a Sustainability Report, has been introduced and holds promise of communicating the positive attributes of an ecosystem approach to aquaculture. Recommendations for transitioning British Columbia aquaculture to an EAA model include: (i) ensuring an appropriate geographic definition of the ecosystem boundaries; (ii) establishment of quantifiable goals and objectives for the EAA; (iii) use of quantitative indicators/metrics to cover all of the social-ecological attributes of the system; (iv) include results generated from these metrics to develop Performance information; (v) ensure effective communication among agencies and the public; and (vi) encouraging innovation through performance incentives.

Introduction

The global pressures on wild fisheries resources, exacerbated with the significant and increasing demand for seafood, has stimulated a spectrum of growth and innovation within the worldwide aquaculture industry. Canada, which supports the world's longest coastline, largest freshwater system, greatest tidal range, and most diverse coastal physiography, would appear well positioned to meet the challenges of increasing the global seafood demand through the expansion of aquaculture. However, in recognizing the inherent need to adequately balance the environmental and socio-economic carrying capacity factors that can ensure sustainable aquaculture development, Canada is in its current, complex position of self-analysis and regulatory/governance reform.

This document uses the Canadian situation, and coastal British Columbia in particular, in a *case study* of aquaculture carrying capacity issues – illustrating how this jurisdiction currently manages aquaculture site selection and operations, and how ongoing changes to its overarching policy and regulatory processes relate to the development of an ecosystem-based approach to aquaculture in this jurisdiction.

Why British Columbia?

There are a number of reasons why one would choose the west coast of Canada – British Columbia – for this *case study* exercise. Despite its globally-recognized reputation with respect to social-environmental conflict, this western region's aquaculture production (and associated economic value) is the largest in the nation. Export of over 85 percent of British Columbia (as with all of Canada's) production occurs to the United States, and hence market-driven change to aquaculture "acceptance", as an important social-ecological food production system, will truly reflect a North American perspective on the future of sustainable aquaculture in this hemisphere.

From a physical perspective the coastline of British Columbia is highly complex, represented by over 25 725 km of coast, shallow to deep inlets (fjords), high and low energy tidal passages, and more than 40 000 islands (of various sizes) extending from the Washington State to the Alaska border. This cold-water environment, similar to that of the Kingdom of Norway and southern Chile, is extremely rich in habitat and species diversity, many of which continue to support a variety of fisheries – but none alone can supply the growing export demand. It is this diversity of aquatic life that also represents the potential for significant aquaculture growth, with the regional government identifying over 80 local species that could be considered as aquaculture production candidates in the future.

Socially, British Columbia aquaculture is faced with a complex mosaic of coastal stakeholders, and the issues and interactions among these stakeholders are considered and integrated into the management framework of this social-ecological system. The use of Crown Land (government-controlled land and the nearshore aquatic base) include such activities as forestry, mining, recreational and commercial fisheries, tourism, and community development – these and other uses often compete for space through regional planning exercises and/or interact environmentally to exclude other, more sensitive activities from development opportunities.

Inclusion of coastal aboriginals, or First Nations, add yet another layer of complexity to the social-ecological aquaculture systems of British Columbia. This region of Canada supports 25 distinct First Nation peoples with over 100 tribes/bands that have documented territorial claims to a variety of coastal resources – particularly to traditional use of many of the area's valued littoral and shallow sub-littoral species. Consideration of Traditional Ecological Knowledge (TEK) within these coastal communities, historical ceremonial uses, and present day subsistence fisheries represent critical social factors that affect how and where aquaculture can be developed.

With a production environment considered ideal for a wide range of aquaculture species, an extensive coastline that could support significant aquaculture development and expansion, and a complex social net of coastal stakeholders (including the traditional, cultural uses of First Nations), the balance of these social-ecological factors represents both regional (British Columbia) and national determinants for site selection, carrying capacity and sustainable aquaculture development practises in Canada – and in application an Ecosystem-Based Approach to aquaculture.

Regulatory and governance framework

The primary responsibility for Canadian aquaculture management is shared between regional (Provincial) and national (Federal) levels of government. Recently (December/2010) the regulation and licensing of aquaculture activities (finfish and shellfish) has been transferred completely to the Federal government – led by the Department of Fisheries and Oceans (DFO) – while the Province of British Columbia maintains control and responsibility of the Crown Land allocation for coastal aquaculture. A new Canada–British Columbia Memorandum of Understanding (MOU) with respect to aquaculture is being negotiated and is expected to layout new roles and responsibilities for each of the parties.

The *siting application* for a new aquaculture tenure (lease) is a proponent-driven process in British Columbia. The aquaculture proponent identifies a potential farm site that is suitable for the species being considered for the development, identifies potential and local stakeholder conflicts associated with the proposed location, and then (if direct consultation with stakeholders resolves any identified conflicts) completes a detailed biophysical appraisal of the proposed farm site, listing and discussing all impacts associated with the proposed level of production, the configuration and orientation of farm infrastructure, the operational risks and emergence response plans, and specific management practises for all activities.

The application for an aquaculture site comprises a standard format and a comprehensive list of information requirements (see following section on Decision Support Tools – Site Specific Management) that jointly form a *Management Plan* for the proposed operation, and the basis for the subsequent review and adjudication. This information typically includes a variety of maps (GIS) delimiting and overlaying the proposed infrastructure works in relation to local aquatic resources and sensitive habitats, wildlife use, adjacent stakeholder activities (aquatic and upland), projected spatial and temporal operational impacts (determined through model projections), site physiography, oceanographic conditions and seasonal water quality, etc.

Aquaculture site tenure/Lease allocation

The completed *Management Plan* developed for a new aquaculture facility is submitted to the Provincial (regional) government for review and ultimate approval. Ensuring that all required information is contained in the application, the packages are then referred out to all potentially affected stakeholders for comment and identification of outstanding issues/concerns – local/regional/federal government agencies, local industry sectors and/or businesses (including adjacent aquaculturalists), local communities and First Nations, and the general public (through media notifications). All parties are given a period of time to respond with their comments/concerns which are then dealt with by the proponent – addressing the issue(s), satisfying the respondent if possible, and reporting the outcomes back to Provincial Lands office.

A key Federal role in the Site application process occurs as part of the above referral process. Under the Canadian Environmental Assessment Act (CEAA) each new farm site application is usually reviewed with respect to all positive and negative environmental, and socio-economic consequences associated with the proposed development. The '*triggered*' CEAA is coordinated by the Responsible Authority

(RA), which is typically Transport Canada (triggered by concerns under the Navigable Waters Protection Act – NWPA) or DFO (triggered given the habitat protection provisions under the Federal Fisheries Act).

Results of the CEAA screening are forwarded to the Province and support issuance of a Crown Land tenure/lease or, alternatively, document why the farm site application should be denied. This key federal referral response, as well as those received from all other stakeholders, are considered in the tenure issuance process. If a positive outcome the Province issues the Aquatic Land tenure (lease) – for the specified purpose only – for a period ranging from 5–25 years (renewable).

Operational regulations

In 2009, the British Columbia Supreme Court released a decision finding that "finfish aquaculture" is a "fishery," and thus falls within the exclusive jurisdiction of Canadian Parliament under subsection 91(12) of the *Constitution Act, 1867.* As a result, it ruled that the majority of the provisions of the existing provincial aquaculture legislation lie outside the constitutional jurisdiction of the province, including those pertaining to fish, shellfish and all other invertebrates – marine plants were exempted from the ruling.

In considering and developing a new regulatory regime under the federal Fisheries Act, which was ruled by the Court to be in place by 18 December 2010 (completing the transition from Provincial to Federal jurisdiction), the Canadian government has considered the importance of covering a number of elements which would otherwise be missing as a result of this ruling: (i) aquaculture licensing for the purposes of regulating the sector; (ii) farmed fish containment issues; (iii) fish health and sea lice management; (iv) waste management, as it applies to protection of fish and fish habitat; and the (v) release and deposit of deleterious substances.

The proposed Regulations (currently under final review before implementation), together with applicable provisions of existing federal regulations, are anticipated to create a regulatory regime that will ensure the proper management of aquaculture, particularly with respect to protection and conservation of fish and fish habitat (an ecosystem approach), in an open and transparent manner. "Management plans and supporting operational policies and guidelines, greater visibility of compliance efforts, increased public reporting of compliance and environmental performance data, and commitment to improving environmental performance will be expected to contribute to improved public confidence in the sector".

Supporting the implementation of the new DFO regulatory regime, there will be program policies and Integrated Management of Aquaculture Plans (IMAPs), modelled after the Integrated Fisheries Management Plans currently used by DFO in other fisheries. The IMAPs will publicly document management objectives for each major sector (e.g. finfish, shellfish), and identify specific operational directives and other matters as appropriate for the management of the sector. DFO proposes to develop IMAPs at the *area level* for key species (such as salmon) to support consideration of cumulative impacts. The IMAPs will eventually be used to set detailed license conditions. IMAPs and operational directives will be consistent with national guidelines, respect other national and regional departmental priorities, and will integrate advice from stakeholders.

The new Aquaculture License will consolidate a number of previously 'permitted' activities, providing some level of increased management efficiency. Each license will identify culture species and be accompanied by site-specific conditions with additions of the license that would be imposed. The conditions will include: (i) measures to minimize escapes, introductions and transfers, incidental catch, predator control, impacts to fish and fish habitat, fish health, sea lice, etc.; (ii) monitoring requirements; and (iii) record keeping, notification and reporting.

Problems and Constraints

While the developing regulatory framework for aquaculture in western Canada, in its application, has access to much of the social and ecological information required to support an ecosystem-based management approach, primary responsibility and governance of this aquatic food sector as a *fishery* rather than a farming activity may lead to a suite of potential conflicts of interest, inefficiencies, and possible judicial challenges. Development of legislation specific to aquaculture (e.g. an Aquaculture Act) may alleviate many of these governance issues, and like other countries that have adapted this approach, allow for the integration of appropriate siting and operational factors into a consolidated and comprehensive approach for managing a socio-economic and environmentally sustainable industry.

Decision support tools

Aquaculture site selection, review and approval in British Columbia is supported with tools that comprise a combination of coastal resource information databases and detailed site-specific assessment and evaluation. The combination of these approaches is intended to address coastal zone management issues (resource allocation) as well as providing criteria (and guidelines) for satisfying concerns over carrying capacity – cumulative impacts of the sector development.

Coastal zone management and aquaculture site selection

British Columbia has been collecting coastal resource information/data in a systematic and synoptic manner since 1979. The resource data collected is quality controlled by a peer-reviewed provincial Resource Information Standards Committee, using standards developed specifically for data management and analysis. The British Columbia Coastal Resource Information System (CRIS) is an Internet-based interactive map for viewing coastal and marine data. A wide variety of coast and marine resources are included, such as aquaculture, shoreline classification, habitat and selected fisheries information, and key human use attributes. The currently available map CRIS information is presented (Box 1).

Much of the provincial coastal resource (CRIS) data are freely accessible and can be viewed or downloaded from a general user perspective or from that of a GIS user, the latter including appropriate formatting for integration into specific mapping applications. See the following web portal: http://webmaps.gov.bc.ca/imf5/imf.jsp?site=dsscoastal. Access to these data, by an aquaculture proponent, are used in an initial screening sense to facilitate the site selection process – identifying local stakeholders, sensitive habitats or other potential social or ecological conflicts that may preclude the siting and subsequent operation of an aquaculture facility in a proposed location.

Development of the British Columbia Coastal Resource Information System is ongoing. The application provides access to data currently held on Land and Resource Data Warehouse (LRDW). As additional layers are added to the LRDW, subsequent releases of the application include these additional layers and further enhancements. One such layer, specific to aquaculture, comprises the broad scale evaluation of shellfish aquaculture capability. Initiated by the Province in the mid 1990's this initiative, completed over a five-year period, assessed all of the intertidal and subtidal area in terms of the biophysical conditions that determine the ability of an area to successfully support various species and approaches of culture, i.e. deepwater oyster and scallop culture, and intertidal (beach) culture of oysters or clams.

A Shellfish Capability Index (SCI) was developed (Cross and Kingzett, 1992) to integrate the various biophysical parameters in a weighted species model of projected site culture capability performance. Extensive field surveys, conducted during seasonal extremes (winter and summer periods), were used to acquire basic biophysical information on all beaches and waterways of the province. The SCI model was then

BOX 1

Available data in CRIS, the British Columbia Coastal Resource Information System-Coastal Data Index. (January 2011)

AQUACULTURE
- Fresh water aquaculture farms
- Marine finfish aquaculture farms
- Salmon aquaculture suitability rating
- Seafood processors
- Shellfish aquaculture capability
- Shellfish aquaculture farms
- Shellfish hatcheries

BIOPHYSICAL SHORELINE CLASSIFICATION
- Biophysical shoreline

BIRD HABITAT
- Alcids
- Bald Eagles
- Black oystercatchers
- Commorants
- Dabbing Ducks
- Diving Ducks
- Fulmars, shearwaters and petrels
- Geese and swans
- Great blue heron
- Gulls
- Loons and grebes
- Shorebirds
- Pelagic birds (unspecified)
- Water fowl (unspecified)
- Bird colonies/nesting sites (excluding Bald eagles)

FISHERIES, COMMERCIAL
- Anchovy
- Crab
- Geoduck
- Goose bamacle
- Ground fish
- Herring food and bait
- Herring rose
- Octopus
- Prawn
- Salmon (net)
- Salmon (trawl)
- Scallop
- Sea cucumber
- Shrimp
- Squid
- Red and green sea urchin

FISHERIES, RECREATIONAL
- Crab
- Finfish (includes sport salmon)
- Groundfish
- Prawn
- Scallop
- Squid

FISHERIES, OTHER
- Clam beaches
- Herring spawning segments
- Salmon and herring holding areas

MARINE ECOSYSTEM CLASSIFICATION
- Marine ecosections
- Benthic ecounits
- Pelagic ecounits

MARINE MAMMALS
- California sea lion distribution
- Dall's porpoise distribution
- Gray whale (migrating and resident) distribution
- Harbour porpoise distribution
- Harbour seal distribution
- Humpback whale distribution
- Killer whale distribution
- Northern fur seal distribution
- Pacific white sided dolphin distribution
- Sea otter distribution
- Californian and steller sea lion haulout areas
- Sealion rafting areas
- Steller sea lion distribution

MARINE PLANTS
- Ealgrass distribution
- Kelp distribution

OFFSHORE OIL AND GAS
- Aeromagnetic
- Climate stations
- Cruiseship routes
- Explorations potential
- Exploratory well's
- Gravity
- Oil and gas tenure – Povincial
- Oil and gas tenure – Federal
- Sedimentary basins
- Sponge reefs
- Tanker exclusion
- Territorial (200 mile) limit
- Bedrock
- Faults
- Grid blocks
- Seismic lines
- Basins

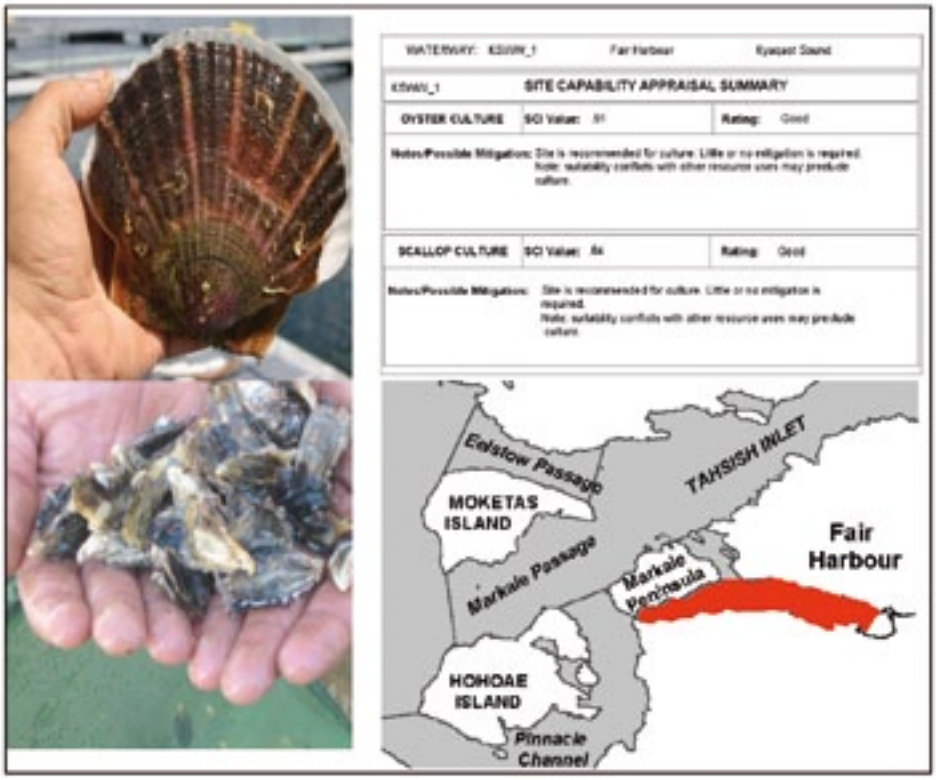
HUMAN USE
- Airports
- Anchorages
- BC Ferry terminals
- Boat cruising routes
- Boat launches
- Campsites
- Diving sites
- Marine Industries
- Kayak route destination points
- Marinas
- Marine hazard points
- Marine hazard lines
- Moorages
- Navigations aids
- Kayaking routes

Source: CRIS, the British Columbia Coastal Resource Information System- Coastal Data Index. (January 2011).

applied coast-wide to provide a general overview as to what specific areas might be best suited to shellfish aquaculture – but solely from a biophysical perspective. Nevertheless, this type of tool provides an important spatial addition to the coastal zone management database inventory and assists both proponents and government regulators that are charged with Management Plan reviews for new aquaculture sites.

Figure 1 illustrates the results for a location (Fair Harbour, shown in red) in which a proponent might be interested in developing a scallop farm. Based on the survey the SCI was calculated as 0.84 and the area is rated as *Good*. While indicating that the area is considered highly capable of growing scallops, the associated note also makes it clear that this activity must also be considered with respect to other stakeholder activities.

FIGURE 1
Example of shellfish (oysters, scallops) deepwater aquaculture capability appraisal for Fair Harbour, west coast of Vancouver Island, British Columbia, Canada



Note: Entire coast completed for both intertidal (beach) and deepwater shellfish opportunities and maintained as part of the Provincial Coastal Resource Information System with GIS maps is accessible to all proponents.

Source: CRIS, the British Columbia Coastal Resource Information System- Coastal Data Index. (January 2011).

Given the extensive area of coastal British Columbia that is capable of supporting aquaculture, yet remains undeveloped in this regard, the issue of aquaculture carrying capacity – at least in terms of multiple farm site effects – are recognized but are a lower priority. However, government has established guidelines for spatial separation for finfish farm operations, applied to address the potential issues of disease transfer, sea lice interactions along migratory routes of wild salmon, and cumulative nutrification impacts. Similar spatial separation has not been considered for shellfish operations, although concentrated development of shellfish in two coastal regions have resulted in site-specific research projects into ecosystem effects (primary productivity impacts) given the intensification of shellfish production – no negative effects were documented in these situations.

Site-Specific Evaluation

While the evaluation of aquaculture operations in terms of carrying capacity are not explicitly implemented within the farm siting process in British Columbia, the production-related review does incorporate considerable detail with respect to site operational effects related to farm size (production levels), farmed species, infrastructure configuration/orientation with respect to oceanographic patterns, site physiography, etc. Farm siting must not have a negative impact to fish or fish habitat, as specified in the habitat provisions of the Canadian Fisheries Act, and specific infrastructure siting and operational guidelines have been established (and are under modification/review under the new regulations).

The proximity to sensitive and/or critical fish and fish habitat, and the dispersion and accumulation of wastes generated from an aquaculture facility, are the two key issues considered in the site-specific evaluation for initial siting and ongoing operational monitoring of aquaculture facilities, respectively. Detailed habitat (biophysical) surveys are required prior to site installation to clearly delimit the spatial extent of all littoral and sublittoral attributes of a proposed farm site, i.e. bathymetry, substrate composition, biological community structure, and oceanographic characteristics. Subsurface attributes are typically documented using remote operated vehicles (ROV's) and/or divers. Tidal activity of a site is determined through deployed current meters (2–3 meters over a lunar cycle) and an optional circulation survey.

All of the information acquired prior to a farm site installation are geo-referenced and integrated into a site map (GIS) showing proposed infrastructure position with respect to all of these biophysical data as well as the archived social (stakeholder) information (e.g. CRIS data). None of the infrastructure associated with an aquaculture operation (shellfish or finfish) can be positioned over any valued ecosystem component (e.g. critical or sensitive habitats such as eelgrass beds, kelp forests, fish spawning grounds, bivalve beds, corals, sponge complexes, etc.).

In the case of finfish farms, where required feed inputs to the system are associated with significant levels of organic waste discharge, DEPOMOD model (Cromey, Nickell and Black, 2002) runs using the site acquired oceanographic, bathymetric and proposed production information are completed under average and maximum feed input scenarios to predict spatial patterns of waste deposition around the farm facility. Regulatory guidelines currently require that no predicted deposition >2.0g C/m^2/day occur inshore of the 30-meter depth contour to avoid all potential impacts with shallow subtidal communities, and that predicted levels >5.0g C/m^2/day not persist at any location beneath or in the immediate vicinity of the farm itself.

Operational monitoring requirements

In addition to fully supporting all forms of Best Management Practises (BMP's), a structured environmental monitoring program is a regulatory requirement of all finfish farms in coastal British Columbia – there is no similar application in the shellfish sector. The finfish program is Performance Based, and focused on environmental loading of organic wastes generated from the farm. The benthic monitoring requires that physical-chemical surrogates of biological response (i.e. sediment sulfides, REDOX) remain below specified performance thresholds prior to fish entry to the farm, and again (at a secondary performance threshold) during the period of peak biomass within the farm system.

The application of a performance-based approach to environmental monitoring and regulatory compliance provides an inherent incentive for production innovation – devising approaches to ensure compliance is achieved while maintaining or increasing farm productivity. For example, one British Columbia company has achieved commercial status for its integrated multi-trophic aquaculture (IMTA) system – an ecosystem approach to aquaculture system design – and is currently operating to reduce the environmental effects of discharged organic and inorganic wastes while increasing its profitability through its multi-species sales (see www.SEAvisiongroup.ca).

Sustainability reporting

Until very recently, the focus on 'sustainability' has been one that has dealt almost exclusively with environmental performance. In Canada, with the recent shift to a federal lead regulatory agency, recognition of the combined social-ecological attributes of aquaculture has resulted in the development of a Sustainability Reporting initiative that has garnered support from a number of industry associations.

Objective: To demonstrate aquaculture sustainability with regard to economic, social, and environmental performance, and to engage Canadians in addressing the sustainability concerns.
Coverage: Use of multiple sustainability indicators (economic, HR, food safety, environmental) – potentially more than 22 specific metrics (license, production, value, compliance, value added proportion, employment, exports, traceability, therapeutant use, BMP, FCR, disease, certification, etc.)
Reporting Frequency: Annual – every spring beginning from 2010
Reporting Agencies: DFO and Statistics Canada

Gap analysis

While not explicitly referring to the aquaculture Siting and Carrying Capacity evaluations as an Ecosystem-Based Approach, the British Columbia process does ensure that these components of sustainability are addressed and that they in fact comprise many of the attributes of these complex social-ecological systems. Weaknesses, or gaps, in this Canadian process can be assessed independently – addressing ecological (production-related) siting and carrying capacity issues, and also the social aspects.

Ecological-related carrying capacity

Although farm siting in British Columbia provides the proponent and regulator with access to a broad range of databases and information on stakeholder and resource use, and provides limited guidelines on spatial separation between fish farms (only) and from sensitive or critical habitat, there is no objective process in place to assess the cumulative consequences of these multiple activities and the effect of including any new development into the system. An effective assessment of carrying capacity, and one that supports a goal of ecosystem-based management should be inclusive of all coastal activities and the potential cumulative effects of their coexistence in an area.

Use of DEPOMOD to predict the spatial extent of organic waste discharge, and the potential interaction with the biophysical environment is applied to finfish farms, and focuses on settleable material only. The effects of deposition from suspended shellfish facilities are also relevant and the dissolved nutrient (inorganic nitrogen) losses from aquaculture should also be assessed in the context of carrying capacity.

Performance Based monitoring metrics, designed to ensure aquaculture operations have limited spatial and temporal effects (impacts) on the receiving environment, are again focused on the localized benthic response and are employed for finfish sector only. The extent of water quality effects and the potential for cumulative impacts are missing from ongoing assessments.

Social-related carrying capacity

The recognition that socio-economic factors play an important role in the development of sustainable aquaculture has grown steadily over the past decade. Inclusion of open public consultation, and consideration of all stakeholder activities and potential operational conflicts, are a routine part of the farm siting process in coastal British Columbia. A critical weakness in this process is in how the values and experience (traditional ecological knowledge) of First Nation peoples can and should be integrated into the farm siting and carrying capacity assessment process. These groups remain intimately connected to the coast – many still residing in remote communities, reliant upon resource-based livelihoods – yet they are often marginalized when it comes to resource allocation and development-related decision-making. An approach for aboriginal participation in the social-ecological aquaculture system would strengthen the transition to an ecosystem-based aquaculture approach.

The development of an industry *Sustainability Report* provides a positive approach to quantifying industry performance, and hence moves to address the social license

issues that have historically hindered aquaculture development in coastal British Columbia. Addressing not only the environmental performance of the industry, this type of initiative can illustrate the significant socio-economic impacts associated with a sustainable aquaculture industry. Current problems in the development of such performance indicators include the limited nationwide statistics on aquaculture, the comparability of data among government agencies (as well as accessibility), and the inherent difficulty in meeting the demands of the public, eNGOs, and the media.

Recommendations

"*An ecosystem approach for aquaculture (EAA) is a strategy for the integration of the activity within the wider ecosystem in such a way that it promotes sustainable development, equity, and resilience of interlinked social and ecological systems*". Soto *et.al.*, 2007

The British Columbia case study would suggest that many of the pieces required of an ecosystem approach for aquaculture are in place but are perhaps not yet integrated into a process that recognizes it as such, or one that is actively making the changes required to meet the broader goals of such an approach. In moving forward and taking the initiative to facilitate the development of the ecosystem approach to aquaculture (EAA), it is recommended that five key issues be concurrently addressed.

- Define the geographic boundaries of the ecosystem.
- Establish quantifiable goals (long-term) and objectives (short term) for the EAA and include a process to support continual improvement.
- Identify and use specific, quantitative indicators/metrics that represent all of the social-ecological attributes of the system.
- Include environmental, social and economic information to evaluate and report on EAA performance, associated management decisions and options.
- Ensure inter-agency and inter-government cooperation and communication as well as an open public consultation process.
- Encourage industry innovation through the application of performance incentives.

Conclusion

British Columbia is collecting a variety of information in support of an ecosystem-based management framework for aquaculture. Consistent application and integration of these environmental and socio-economic data into the operational stages of a performance-based regulatory model will encourage industry-driven innovation as we strive for globally sustainable seafood production.

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Regional and national factors relevant to site selection for aquaculture in the Federative Republic of Brazil

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Abstract

Aquaculture and Fisheries Production in the Federative Republic of Brazil has been steadily growing in the past decade. Recent official figures report 1 240 813 tonnes for 2009. Aquaculture growth in the 2003–2009 period has been 49.4 percent, from 278 000 tonnes in 2003 to 415 000 tonnes in 2009. Recently, aquaculture growth (from 2007–2009) has been even more expressive at 60.2 percent. The main cultured species is tilapia, which accounted for 132 000 tonnes in 2009, about 39 percent of all cultured fish in the country. Marine shrimp production has been stable at 60–70 000 tonnes/year. Aquaculture feeds produced in 2009 is at 300 000 tonnes for fish and 80 000 tonnes for marine shrimp. These numbers reflect the optimism felt by entrepreneurs in the aquaculture/agribusiness sector. This scenario is in good part due to steady, although slow necessary improvements in the environmental and aquaculture production policy and legislation.

Regional and national factors relevant to site selection for aquaculture

Ecology – Limnology

The Federative Republic of Brazil is a country of rivers, not lakes. However, the use of over 5 million hectares of water surface in reservoirs of hydroelectric power plants available for cage culture production of fish presents a significant potential. These waters are mostly found in the reservoirs of hydroelectric powerplants. This potential is seen by the government as having good potential for fish production, and demonstrates interest in facilitating participation of the less privileged social classes residing in the countryside along the perimeter of these reservoirs. The use of close to these waterbodies poses some challenges. Another type of large reservoir built in the past was that primarily aimed at the alleviation of droughts. These are typical of Northeastern Brazil, have been and are used for fish farming and fish stocking but nowadays are mostly considered eutrophic and/or contaminated. Their primary function has from the onset been the alleviation of human suffering, by providing water for humans and livestock. Beginning in the 1970s these reservoirs were populated with fish as a an alternative to provide local populations with a protein source. Aquaculture intensification efforts in these areas is a constant. Hydroelectric power water reservoirs

and their public waters as an alternative support for aquaculture have been only recently (2000s) been in higher demand. Because of the nature of their construction and end use, hydroelectric power plant reservoirs have a particular limnology which is quite different than that of natural standing waterbodies. The water renovation characteristic, for example is different from that of a natural lake. The flushing rate of these reservoirs is regulated by human control, mostly in function of meteorological forecasts. Most of the water that flows out of the reservoir comes from the lower strata of the waterbody rather than from the surface. In large reservoirs such as Itaipu, some areas of the waterbody experience oblique vortexes from the water surface to the turbine intakes which have create very different vertical water quality parameter distribution than those found in 'normally' stratified waters in. Natural cycles may not be comparable to the 'great' lakes found in temperate climates common in the northern-hemisphere. Given the growth trend of the Federative Republic of Brazil predicted for the future years and its extensive hydrographic basins and energy potential it is natural that more dams will be built. Local human settlements and populations from the future flooded areas of these watersheds will be relocated to the perimeter of the new reservoirs. These settlers are the new stakeholders in this water resource.

Democracy and legislation

It has been only 25 years since the 1985 'restoration' of democracy. The country was under military rule for a 30 year period (1964 – 1985). This return to democracy has been marked by several changes in governance at many levels. Established institutions ruling and responsible for sectors such as fisheries have dramatically changed with some progress in terms of their attributions, but with significant dispersion of human resources. Trained scientists acting in the fisheries sector were displaced to other sectors. Focus also changed from a more industrially inclined one where issues such as pollution and environmental degradation were not considered as important in the 1980's. With the environmental awareness brought about by the Earth Summit – United Nations Conference on Environment and Development (UNCED) 1992, held in Rio de Janeiro, awareness in all sectors dealing with the environment began shifting to conform. It can be said that as a consequence the aquaculture and fisheries activities became a special Secretariat and an independent one in 2003, completely detached from the Ministry of Agriculture. In 2009, the Special Secretariat (SEAP) became a fully-fledged Ministry – the Ministério da Pesca e Aqüicultura (MPA). This consolidation of public policies has led to more confidence and investment in the sector.

Currently there are 6 hydroelectric power plant reservoirs already regulated with carrying capacity studies concluded. 14 other reservoirs are undergoing carrying capacity studies for the establishment of Aquatic Parks (areas reserved by the state for the development of aquaculture, which may contain several Aquatic Areas) and Aquatic Areas – areas within the Aquatic Parks leased to individuals or groups for aquaculture development. Areas in an Aquatic Park and in between Aquatic Areas may be used for 'compatible' activities such as Fishing.

Still, 25 reservoirs are undergoing the demarcation process covering a total of 1.6 million ha of water surface and 2 600 ha of Aquatic Areas for production.

The legal process currently established by the MPA has become a clear one for prospective aquaculture entrepreneurs with a roadmap to follow detailing the proper documentation to submit, simplifying what used to be a relatively confused process involving multiple permits with different federal agencies including the Navy. Today, thousands of groups and individuals actively practice aquaculture still without a legal permit, however reasonably sure they will obtain a full permit in the near future.

A brief summary of the more recent pertinent legislation:

- 1997 – *Resolução Conama 237* – Establishes the legal base for environmental licensing of aquaculture.

- 2003 – *Decreto 4895* – establishes conditions for Aquaculture development which must observe several criteria including sustainable development, increase in fisheries production, social inclusion and food security.
- 2004 – *Instrução Normativa 6* – lays down most basis for aquaculture projects to be managed by Aquaculture and Fisheries Secretariat as main responsible party.
- 2005 – *Instrução Normativa Interministerial #7* – establishes a max of 1 percent occupancy of public waters for aquaculture use, and guidelines for cage culture in respect to depths.
- 2005 – *Resolução CONAMA 357* – establishes max limit of 30 µg/l for TP and Cla for Aqüicultura in lentic waters.
- 2007 – *Portaria 237* – Allows for the leasing of public Waters to the Aquaculture and Fisheries Secretariat, who can then sub-lease to prospective aquaculturists.
- 2009 – *Resolução Conama 413* – Is the most complete update on the regulations for aquaculture. It basically establishes environmental licensing conditions for aquaculture for: Fish, freshwater shrimp/ prawns, molluscs, seaweed, frog. It levels rules for the concession of licenses. Minimizes pollution effects of large-scale aquaculture. It applies to any level of environmental aquaculture licensing with no losses to licensing request procedure rules already established at more regional scales such as state or municipal levels which may consider specifics of local environments. It defines the sizes of Aquaculture operations and Potential Severity of species.

Identifying issues locally specific to species, cultures, and geographies

Species

Many tropical countries such as the Federative Republic of Brazil, have a large variety of potential aquaculture species within its fish biodiversity. Domestication of species however, aquatic or not, takes decades, if not centuries. The common carp was the first species of fish to be introduced for culture purposes in the country. Its success in part is due to the familiarity of European immigrants and their descendants such as Germans and Italians. For similar reasons rainbow trout culture also became quite popular in southern states, but mostly constrained to sites at least 700 m in altitude. Although tilapia is the main species produced in the country, progress is being made with native species such as *tambaqui* (*Colossoma*), and *pacu (Piaractus mesopotamicus)*. Tambaqui production is steadily on the increase and now at about 46 000 tonnes/year. All of marine shrimp production is based in the exotic *Litopenaeus vannamei* which has been stable at around 70 000 tonnes/year, most of it destined for export. Other cultured species include some South American striped and spotted catfishes, mostly destined for the internal market, pacu (*Piaractus mesopotamicus*) and to a very limited extent channel catfish (*Ictalurus punctatus*), in southern, lower latitude cooler climates such as found in the state of Paraná.

In regards to marine species the most prominent is the brown mussel (*Perna perna*) and the Pacific oyster (*Crassostea gigas*). To a lesser extent, the native scallop (*Nodipecten nodosus*) and marine algae *Gracillaria spp* and the exotic *Kappaphycus alvarezii* are cultured more or less intensively. Still on an experimental basis are a few initiatives with cobia – *Rachycentron canadum*. Other species currently being researched include snook (*Centropomus spp*), octopus, and sea bass, but still at experimental level.

Although aquaculture represents only 5 percent of animal production in the Federative Republic of Brazil, its annual growth rate is higher than that of poultry (10 percent), cattle (4 percent), pork (7.9 percent), soybeans (8.6 percent), corn (7.6 percent), wheat (13.4 percent) and rice (3.4 percent). The Federative Republic of Brazil is the 4th country with highest annual aquaculture growth rate at about 23.3 percent a year.

It was only in the mid 1980s that the awareness of the country's fish diversity had some potential to contribute to fish farming, and experimentation with some native species began. Despite great progress in establishing conditions of reproduction and grow-out practices for native species like *tambaqui* and *pacu*, the impact of hybrid tilapia culture introduced since the 1970s in Northeastern Brazil had already made its mark on the national scenario. Today most, if not all states of the Federative Republic of Brazil have tilapia farming across the many hydrographic basins of the country. Brazilian funding for aquaculture research has increased significantly by interministerial agreements and the Brazilian National Research Council (CNPq). However, it is quite difficult for it to compete with international funding for farmed tilapia improvement. The most recent genetically improved varieties developed at leading aquaculture centres throughout the world soon become available in one way or another in the major aquatic farms across the country. Tilapia culture accounts for over 90 percent of cage culture in enterprises established in the hydroelectric power reservoirs. Since tilapia has become a commodity worldwide, and represents a good export product, its production chain has been officially adopted by the Brazilian government during the last decade. The same can be said for *L. vannamei* white shrimp, a hardy species cultured in several Latin-American countries which has become standard in the Federative Republic of Brazil.

Culture

Apart from early Portuguese colonists and African slaves, colonization in the Federative Republic of Brazil really only picked up at the end of the 1800s. From 1872 (year of the first census taken) to 2000, six million immigrants arrived in the Federative Republic of Brazil, most of which were heading towards Southern Brazil and the coffee plantations where slave labor was being substituted for salaried labour. Most immigrants were of Italian, German, Portuguese, Spanish and Japanese origins.

A marked difference between the newly arrived immigrants and the former indigenous peoples, the early Portuguese colonists and their Brazilian descendants – was the attitude towards food procurement. Whereas the latter were content to behave in a mostly 'extractive' fashion i.e. hunting, gathering, ranching and living on a diet of mostly wild caught animals or ranch cattle meat, the new immigrants were more eclectic in their dietary habits which traditionally consisted of farmed products and also lived in crowded quarters. The new immigrants were primarily interested in working in an agricultural environment, producing their own food and surplus for sale. They were well aware of the importance of food surplus post-harvesting processes. The fewer than 3 million native inhabitants of the Federative Republic of Brazil spread over 8.5 million km^2 before its discovery had little trouble in finding fresh food, and were in many cases, semi-nomadic or nomadic by culture. This may explain in part the reason why, despite lower temperatures and shorter growing season, Southern Brazil has made many significant strides in aquaculture (and agriculture) where as in tropical areas of the country such as North Brazil including most of the Amazon, the activity is still underdeveloped. One short-lived exception to this is what was probably one of the first aquaculture attempts in the New World undertaken by Mauricio de Nassau, during the Dutch control of Recife, North-eastern Brazil (1637–1644). His residence/fortress was designed with large fish ponds.

Geography

The country's coastline spans over 8000 km from 3°N just above the equator, bordering the French Republic (French Guyana) to about 34°S, the frontier with Uruguay. In the East-West axis, longitudes span from 34°W to 74°W, from the Atlantic Ocean to almost the Pacific Ocean, bordering neighbouring South American countries including

Paraguay, Bolivia, Peru, Colombia, Venezuela, Guyana, and Surinam. The continental dimensions of the country present a challenge of distances over several latitudes, climates, soil types in which old world farm stock species have not found similar environments such as occurred for example in North America during its colonial period.

Use of models and decision support tools

Freshwater carrying capacity

Several environmental analysis modelling tools for determining fresh water fish farming carrying capacity are being used in the Federative Republic of Brazil. These include Stella, DELFT3D and MIKE21. For freshwater the most commonly used method is the Dillon-Rigler modified by Beveridge (1984). These studies have been applied to estimate the carrying capacity of cage culture in hydroelectric power reservoirs shown (Figure 1). So far, this method has been found to be acceptable by the Ministry of Fisheries and Aquaculture experts. Due to the particular nature of the waterbodies assessed – mostly hydroelectric power plant reservoirs, and the behaviour of Nitrogen and Phosphorus in these, specialists involved in these studies, such as Drs. Ricardo Pinto-Coelho, Fernando Starling and William Severi, have expressed interest in using a method which would be based on Nitrogen rather than Phosphorus. Starling used the Dillon-Rigler method and compared the results to those from a Stella model developed for the same conditions. Table 1 summarizes the 6 major reservoirs which have so far had carrying capacity studies done and have aquaculture areas set aside for development.

FIGURE 1
Hydroelectric schemes in Brazil where models have been used to estimate carrying capacity

Source: Ações do Ministério da Pesca e Aquicultura. Courtesy of Mr Rodrigo Roubach, Ministério da Pesca e Aquicultura, Brasil

TABLE 1
Aquaculture Areas used in the Aquatic Production Parks in the Federative Republic of Brazil

Concluded demarcation	Reservoir area (ha)	Aquatic Park area (ha)	Aquatic Areas (ha)	Aquatic Areas (%)
Furnas	147 000	2 848	297	0.2
Três Marias	104 000	3 042	144	0.14
Ilha Solteira	123 000	1 352	260	0.21
Castanhão	32 500	7 396	131	0.4
Itaipu	135 000	11 570	31	0.02
Tucuruí	263 500	2 295	115	0.04
Total	805 300	28 503	978	0.12

Carrying Capacity in the marine/coastal environment

Marine aquaculture in the Federative Republic of Brazil is still concentrated in Southern Brazil, and mostly around mussel and oyster production. GIS support and carrying capacity models for coastal areas are still being developed together with the activity itself. The expansion of the shellfish farming sector has been rising steadily, and stakeholders of several different interests in the concerned areas have participated in preparatory discussions and planning meetings promoted by the MPA for the Local Plans for Mariculture Development (PLDMs), such as the one developed for Santa Catarina state in Baía Sul de Santa Catarina, by Florianópolis (W 48°36', S 27°44'). So far, only this coastal state – the largest producer of farmed shellfish in the country – has presented its PLDM to the MPA. The plan was developed by EPAGRI – the state Agriculture extension agency – and based on a GIS model developed by Luis Fernando Vianna which incorporates an Analytical Hierarchy Process for the decision-making which was supported by many stakeholders during several meetings. The participatory approach resulted in the identification of over 130 'descriptors' of influences to the aquaculture activity by stakeholders, and a relative rating of their importance as perceived. However, a proper carrying capacity support model resulting in a shellfish biomass potential tonnage to be cultured was not carried out. The results suggested the best/most proper/acceptable areas for the ministry to 'set aside' for delimitation of the Aquaculture Parks and Aquaculture Areas. The results of this work which began in 2004 were concluded in 2009, with approval of all the aquaculture communities and stakeholders involved in the study. It incorporated the historical oceanographic data available.

Currently two other PLDM's are being carried for coastal aquaculture in the Federative Republic of Brazil. One is being done by NeoCorp Ltda., for Rio de Janeiro state (W 44°30', S 23°10'), and employing MIKE21 software (www.mikebydhi.com/). Another PLDM is being carried out for the state of Bahia (W 38°34', S 12°50') by BahiaPesca the state's fisheries extension service, which is currently employing the DELFT3D (www.deltares.nl/en/) modelling software to understand the hydrodynamics of the Todos os Santos Bay before actually proposing indicated areas for aquaculture development. Bahia has the longest coastline among Brazilian states with over 1 100 km. Both of these studies are guided by the MPA's policy to fully respect environmental aspects, contemplate the sustainability of the activity and suggest harmonious integration of aquaculture with local fisher communities while taking into account conservation of local ecosystems which include abundant mangroves present in Bahia and the traditional coastal fisheries of Rio de Janeiro. However, from the initial information available, an aquaculture potential biomass capacity does not appear to be in formulation.

Main gaps and improvement needs according to the EAA

Difficulties initially faced by aquaculturists in the Federative Republic of Brazil included the lack of specific environmental legislation, existence of costly license fees and public prices above payment ability of small producers. Also, difficulties in being able to handle the complexity of information necessary to the licensing process, a lengthy analysis process, and general impediment of access to 'aqua' credit, as opposed to proponents for agricultural land-based rural activities. Consequently, there was little if any stimulus for investment or entrepreneurship in aquaculture, much less good production practices.

These obstacles have been gradually overcome in updates in legislation especially with the *CONAMA 413* resolution which has better defined parameters, criteria and procedures on a country-wide basis applicable at all levels. Currently there is the possibility of small enterprises to be relieved of licensing, allowing important stakeholders such as fishers and riverside communities to participate in aquaculture production. The possibility of relieving licensing for small enterprises or licensing

the activity by block of enterprises, also allows fishermen and other cooperatives and associations to start up aquaculture. As a result the licensing process tends to be swift and a real incentive for sustainable aquaculture practices and better controlled.

Current and future issues and bottlenecks

The studies so far undertaken to determine aquaculture carrying capacity in the Federative Republic of Brazil have been done mostly for artificial freshwater reservoirs whose primary function is water for hydroelectric power generation. It is then a complex issue to evaluate the 'environmental services' of these relatively recent artificial ecosystems in the context of EEA.

New reservoirs such as the Belo Monte project in the Amazon damming the Xingu river which would be the world's third-largest hydroelectric project poses many questions. There are few studies of similar cases in other tropical countries. These new reservoirs will cover extensive areas and will involve the disruption of several migratory species of freshwater fish including *Colossoma*. This species migrates extensively and has an important role in primary production distribution in the Amazon basin which is still not well understood. It is known that *Colossoma* for in the flooded areas of forests sometimes very distant from areas where it eventually spawns. *Colossoma* die in large numbers in marginal lakes by main rivers in the Amazon thus contributing to the enrichment of these habitats, many kilometres away and downstream from where they feed. In what ways can the EAA take this into consideration? Knowing what the ecosystem's carrying capacity is, and how to share it with human activities and presence within defined acceptance levels still to be defined constitutes a complex problem.

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Ecosystem approach and interactions of aquaculture activities in southern Chile

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Abstract

The main objective of this paper is to understand key, practical and important problems, in relation to carrying capacity of seaweed, caged-salmon and mussel-farm production, respectively, located within the Inland Sea of the Xth region (ISEX), the Republic of Chile. Several interactions between different aquaculture activities in the ISEX have been studied, with particular emphasis in the water column and Harmful Algal Bloom. From an ecological point of view the aquaculture production in the ISEX is composed of 2 major components; photoautotrophic (Seaweeds) and heterotrophic (Mussels and Salmonids). One problem that we have observed is a low mussel yield possibly explained by the lower than normal phytoplankton abundance during 2009 in the ISEX compared with the last decade.

It is important to carry out a marine survey and models to evaluate fate, proportions and balance of the primary nutrients. Only once this is complete can we more accurately estimate the environmental carrying capacity of areas and nutrients that are limiting resource for phytoplankton, and hence for mussels yield. An aquaculture and ecosystem model is required to forecast and verify the different photo-autotrophic and heterotrophic biomass level and the magnitude and fate of nutrients. Assuming that bio-ethanol and marine bio-fuel projects will be successful, in the long term (10 – 15 years), we could observe nutrients depletion in ISEX during summer period, due to large production areas (> 25 000 hectares) of seaweed.

Introduction

This case study is based on an ecosystem approach and the interactions between several marine aquaculture activities in the south of the Republic of Chile. The main **objective** of this study is to understand several key, practical and important problems, in relation with the environmental carrying capacity of caged-salmon and mussel-raft aquaculture sites, both systems located within the same Inland Sea of the Xth region (ISEX) of the Republic of Chile. This case study illustrates the interactions between different aquaculture activities in the coastal zone and inland sea of the South of the Republic of Chile, with particular emphasis in those ecological aspects observed basically during the last decade (Soto and Jara, 2007; Buschmann *et al.,* 2009; Clément *et al.*, 2010).

Aquaculture in South America

Aquaculture in South America and Latin America is quite a diverse activity in terms of species, geography, and technologies among others; however it may be outlined as follows:

During recent years Peru is becoming an important trout producer in fresh waters, and this country has the advantage of being one of the largest fish meal and oil producer in the world. The Peruvian aquaculture industry is, little by little, turning into an important industry and is attracting significant investment. Although it is in an incipient stage, it is steadily growing. In 2007 their production was 39 000 tonnes and by 2009 it grew to 49000 tonnes. In 2010 it is expected to exceed 52 000 tonnes (www.aqua.cl). The Argentine Republic particularly in the south has few fresh waters salmonids aquaculture facilities including cage systems in reservoirs. Ecuador has a well established large shrimp production occupying a significant amount of the surface areas of the coastal zone, but these data will not be analyzed in this case study. Since 2003, the Paraguayan Tilapia industry has grown annually approximately 200 percent and it has more than 2 600 producers and an annual production of approximately 1 000 tonnes (www.aqua.cl).

Arzul *et al.*, 2002 studied the interaction of ecological aspects of several activities in South American countries, with emphasis on noxious phytoplankton. My colleague Dr. Philip Scott will present his results of these aquaculture activities from inland waters of the Federative Republic of Brazil during the workshop.

Regional and national factors relevant to site selection for aquaculture

- National New Regulations. Ley de Pesca y Acuicultura; Aquaculture Environmental Regulation (RAMA), Aquaculture Sanitary Regulation (RESA), Aquatic Pest Regulation (REPLA).
- Environmental Impact Assessment. New institutions; Ministry of the Environment.
- At a Regional level the Integrated Coastal Zone Management has implies new policy in sites selections.
- Historical decisions and concessions policy.

Identifying issues locally specific to species, cultures, and geographies

At present, the salmon farming industry faces a major challenge after the ISA virus outbreaks initiated in the ISEX and region XI during 2007, areas that have been used for salmon-cage farming during the last decades. Note also that ISA virus disease was detected in salmon farms in some sites of XII region.

The precise estimation of the carrying capacity of the fjord systems (for aquaculture activities) and the possible impacts of changes in the carrying capacity of ecosystems poses a major scientific challenge in this pristine region (Iriarte, González and Nahuelhual, 2010; Tapia and Giglio, 2010).

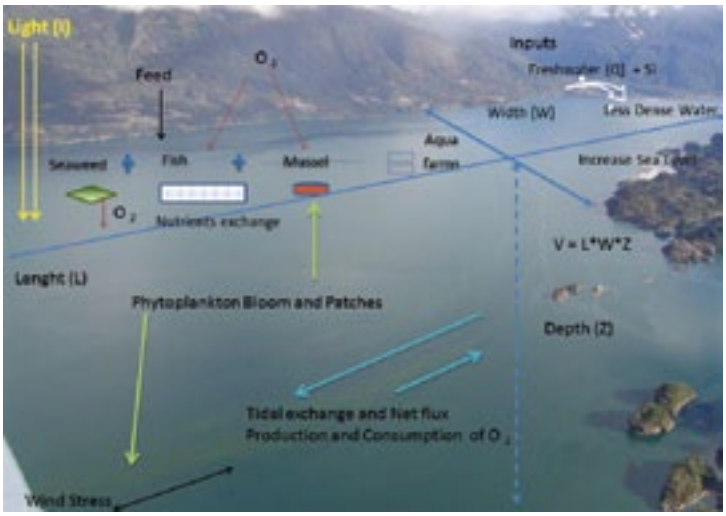
The basic schematic ecosystem model in the ISEX is described in Figure 1 and illustrates the 3 major contributors and their interactions;

1. Seaweeds (*Macrocystis pyrifera* and *Gracilaria*);
2. Mussels farms (*Mytilus chilenis*); and
3. Salmonids (*Salmo salar*, *Oncorhynchus kisutch* and *O. mykiss*).

This basic model, i.e. considering the estuarine circulation, the atmospheric inputs, land pollution effects, and other activities such as salmon, mussel and seaweed farms illustrate a holistic and integrated ecosystem (Soto, 2009). Using this basic model we can estimate the Nitrogen and Phosphorus loading in the ISEX of the Republic of Chile. Also it is relevant to study the Chaitén volcano ash fluxes, the local meteorological and light temporal variability, and the nutrient fluxes between phytoplankton, mussels, seaweed and salmonids; gelatinous zooplankton assemblages' predations/consumption effects; land-sea interactions, particularly pollution problems from waste water.

In: Brooks and Mahnken, 2003 inform that 20.5 – 30.0 g of nitrogen and 6.7 g of phosphorus are released per kilogram of Atlantic salmon produced when fed modern high-energy diets containing 30 percent lipid. Therefore we can estimate the N and P loading, however, we do not know the total budget, fluxes and removals.

FIGURE 1
Basic conceptual model of aquaculture activities and fjord ecosystem

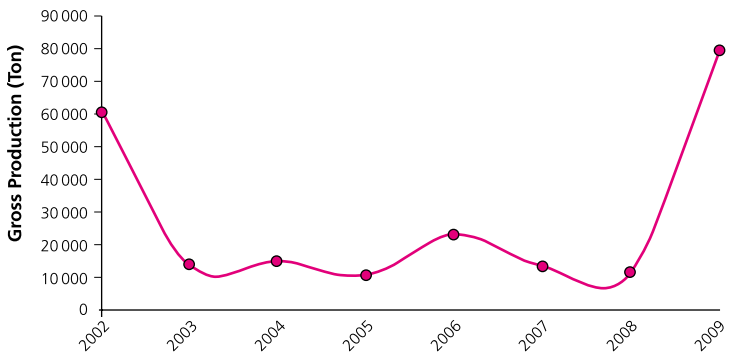


Seaweed culture

During the last 20 years seaweed culture has been dominated basically by *Gracilaria*, but recent new aquaculture projects related with the use of brown-algae biomass and bio-ethanol could change the scenario. These projects are led by BAL Chile S.A and they are culturing the brown alga *Macrocystis pyrifera* in the ISEX. This project has great potential if the cost of production is feasible. It will imply a relevant increase of autotrophic biomass, nutrients and CO_2 uptake or removal and O_2 production. However, this activity will compete with mussel farms for marine space. In addition, from a biological and ecological point of view, nutrient competition (nitrogen and phosphorus) of seaweed culture and phytoplankton assemblages could be observed in the midterm and the environmental carrying capacity for extensive culture – seaweed and mussels – could be observed.

A model is required to forecast and verify the different photo-autotrophic and heterotrophic biomass level and the magnitude and fate of nutrients, in order to establish which nutrients may be a limiting resource. The enclosed graph shows the total seaweed production (Figure 2).

FIGURE 2
Gross production of seaweed in the inland sea of Region X, Chile



Source: Sernapesca. www.sernapesca.cl

Salmonid culture

The salmonid aquaculture industry in the Republic of Chile has been an import economical activity with positive growth rate until 2006. However, after 2006 we observed the most severe crisis due to ISA virus outbreak and the global financial problem at the same time, with losses in fish biomass and an economical impact over US$1 600 000 000.

The main questions that arise are:

Was the Environmental Carrying Capacity (ECC) of the Marine Inland Sea exceeded? However, we do not know the real and potential ECC in the ISEX.

Was this disease outbreak only a sanitary problem and independent from environmental or oceanographic conditions?

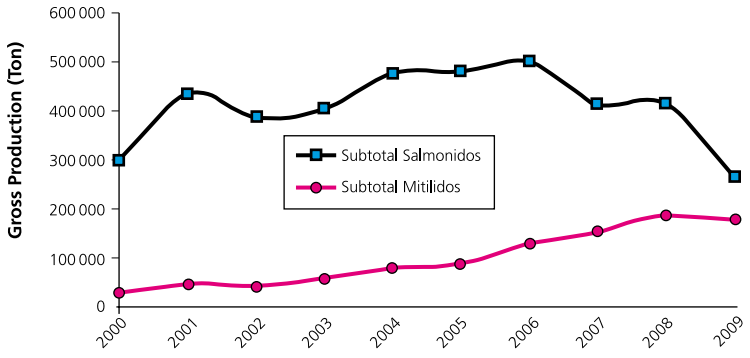
Some key issues that contribute to the crisis were:

a) Many farm sites in small areas or volume of water. The aquaculture and environmental regulations and/or the licenses system authorize the location of sites to close each other.
b) Bad quality of smolts and imported eggs with new diseases.
c) A large biomass production system per site (> 5000 tonnes).
d) A lack of a specific regulation for waste water treatment from salmon processing plant located in the coastal zone.
e) Unusual proportion (*for fish*) of terrestrial vegetable protein and other feed stuffs instead of fish meal and oils in commercial feeds.
f) A not well coordinate logistics and marine transportation issues.
g) Others.

Mollusc culture

Mussel farms and biomass were increased exponentially during the last 6 years; however after 2008 there was decrease in the growth rate (Figure 3). We do not know if the biomass decrease was due to the financial global crisis or an environmental carrying capacity problem or both. During 2008 the total loading of mussels from ISEX aquaculture was around 200 000 tonnes in an area no larger than 8 750 km^2.

FIGURE 3
Gross production from aquaculture in X region, Chile, 2000–2009



Source: Sernapesca. www.sernapesca.cl

In 2009, mussel farmers observed a very low yield (ratio = soft tissue/total weight) of mussels in raft system in many culture sites in the ISEX of the Republic of Chile.

To investigate this, a time series (www.plancton.cl/pal) analysis of inter-annual and spatial phytoplankton abundance was conducted from which it may be concluded that in 2009 there was very low cell abundance in the water column at many culture sites of ISEX.

In addition, a different source of information and a complete 14th -month temporal-spatial phytoplankton monitoring at 3 sites, with replicates showed the same trend (Clément *et al.*, 2010). Therefore, the low mussel yield is possibly explained due to the lower than normal phytoplankton abundance during 2009 in the ISEX compared with the last decade. The 2009 phytoplankton abundance was the lowest in almost a decade and the 2010 spring data shows the same trend.

Why is there a correlation between the low culture mussel yield and strong decrease of phytoplankton abundance during 2009? The hypotheses are:

- An eventual overloading of the carrying capacity of the mussels biomass and culture.
- After June 2007 there was a dramatic decrease in the number of salmon farms in the ISEX area, which resulted in a reduction in organic and nutrient inputs to the water column.
- In May 2008 there was a large eruption of Chaitén Volcano, producing an enormous amount of ash, some of which was deposited in the ISEX (Figure 4).

- Meteorological time's series data indicates that 2009 was a colder year than normal.
- And we speculated the ISEX ecosystem after 2008 had less phytoplankton nutrients due to a combination of oceanographic conditions.
- We believe that is a combination of interactions between the above-mentioned factors, not one factor exclusively.
- While we do not intend to solve the problem here, we believe this is an interesting case of ecological interactions between mussel and salmon farms and biological water column conditions. We will discuss the issue in the workshop.

Use of models and Decision Support tools.

DEPOMOD

This model has been used commercially in the Republic of Chile by several consulting companies (Gargiulo, 2007) and also has been evaluated and compared with field data and others models by academic scientist (Salamanca, *personal communication*), Tironi, Marin and Campuzano (2010). DEPOMOD is a Scottish initiative (Cromey *et al.*, 2002a and b) and has been a useful tool for fish- farm environmental assessment. Locally it was compare with other models, and showed the same patterns, but different dispersal surface area under the cages (Tironi, Marin and Campuzano, 2010).

FIGURE 4
Eruption of the Chaiten volcano in 2008

Image Source: NASA. Processed by Remote Sensing Lab, Universidad de Concepcion, Chile.

COPAS (Centro de Investigación Oceanográfica en el Pacífico Sur-Oriental)

One of the goals of COPAS is to contribute to the knowledge of circulation, water masses and large-scale processes off southern Chile, and the effects of their variability on present and past biological productivity and biogeochemical cycling in the Eastern South Pacific, including the fjords system (www.copas.cl).

The scientists of COPAS have been conducting a large-scale multidisciplinary research project with contributions from several aspects of marine ecology, oceanography and modelling to estimate the carrying capacity of fjords (Iriarte, González and Nahuelhual, 2010; González *et al.*, 2010).

The ECOManage Project: (www.ecomanage.info)

Ecologists and social scientists are presently merging their skills for developing integrated tools to help decision-makers in the difficult task of integrated coastal zone management. EcoManage is a project that aims to push the capacity of assisting managers to merge knowledge from ecological and socio-economic disciplines to better understand:

(1) The variables driving the health of the coastal zone such as local pressures from people, and pressures originating from the drainage basin, transported mostly by rivers and by groundwater;
(2) The socio-economic activities that are important and their impacts on the ecosystem including feedback loops on socio-economics; and

(3) The physical characteristics of the ecosystem that together with the loads determine its ecological state.

Three coastal zones showing conflicting interests between urban, industrial and agricultural pressures and environmental maintenance have been selected for this study. These areas are: Aisén Fjord in the Republic of Chile, Bahía Blanca estuary in the Argentine Republic and Santos estuary in the Federative Republic of Brazil.

Participatory methods will be applied for interaction with stakeholders in order to establishing study scenarios and indexes for social-economic and ecosystem analyses and to measure environmental impacts of management decisions. Field data will be analyzed using a Spatial Decision Support System (SDSS). The models created will help simplify the assessment of the impact of management scenarios and evaluate their performance. The project will improve normative rules for the functioning of the systems, and in this way to improve environmental management for the estuaries towards sustainable development [http://antar.uchile.cl/].

MOHID

Laboratorio de Modelación Ecológica (2012) presents the MOHID modelling system as an excellent framework to develop management tools for particulate waste assessment in coastal marine systems, according to the needs, capacities and requirements of local decision-makers. This system has the ability to synthesize data from numerous salmon farms and their cumulative effects, with relatively low fund requirements, a continuously updated open-source modelling software system and a growing online support community (www.mohid.com), making it an excellent choice to assess environmental impacts of coastal system, especially for developing countries.

In order to improve the usability and acceptance of MOHID's lagrangian module as a solid waste dispersal model for aquaculture, this system requires field validation and it needs to be compared with other models such as DEPOMOD and MOHID in similar scenarios.

Other local Models

A model of the spatial distribution and loading of organic fish-farm waste to the sea bed was used and refined in Dalcahue channel (ISEX). The 90 percent isoline of the sedimentation model marks the boundary of ecologically influenced sediment compared to *in situ* data, considering

I. Carbon content
II. Macrobenthos
III. Redox potential
IV. Metabolic solutes

This indicates a maximum loading capacity of 5 g C m – 2d – 1 for the benthos in the investigated area before an influence on benthos and biochemistry is visible or measurable, respectively. The sedimentation model is a powerful tool to predict organic carbon sedimentation and its distribution over the sea floor, thereby assisting in managing site specific limits. The sedimentation of organic carbon can be spatially correlated to the impact on the benthos; however, it is a conservative measure and is negligible when considering the overall carbon cycle in a fish farm area (Hevia, Rosenthal and Gowen, 1997).

Main gaps and improvement needs according to the EAA

We require a nutrient budget and assessment, particularly for silica, nitrogen and phosphorus, in the ISEX. Once this has been done it will be possible to estimate the relative amounts and inputs of "new production" from aquaculture with those natural fluxes in the sea.

Integration of current approaches with regulation and governance: examples of current practice and problems

Immediately after the ISA virus crisis, new aquaculture and fisheries laws were discussed for more than a year in Congress. These laws have been approved and have had many implications from a financial, sanitary and environmental point of view (Ley General de Pesca y Acuicultura. Última Modificación Ley N° 20.451 F.D.O. 31/07/2010 www.subpesca.cl). One of major changes is a different production system based in a **group of concessions** (*barrios* Clément, 2008) (Figure 5). The system is operating based on organized and coordinate actions; groups of salmon producers have to stock their smolts within a period and area (group of concessions), and they have to harvest the biomass before 24 month of production. After this production system and period the groups of concessions have to fallow for 3 months. The method is commonly called 24+3.

Identifying current and future issues and bottlenecks

- There will be (in the short term 5–8 years) several conflicts due to marine space utilization of the aquaculture activities in the ISEX.
- Assuming that bio-ethanol and marine bio-fuel projects will be successful, in the long term (10 – 15 years), we could observe nutrients depletion in ISEX during spring and summer period, due to large production areas (> 25000 hectares) of seaweed.
- Fresh and marine water quality deterioration.
- Habitat disturbances due to intense use of waterbodies and the coastal zone.

Recommendations

It is important to carry out a marine survey and models to evaluate fate, proportions and balance of the primary nutrients involved in aquaculture activities including photo-autotrophic production. Only once this is complete can we accurately estimate the environmental carrying capacity of areas and nutrients that are limiting resource for phytoplankton, and hence for mussels yield and also for photo-autotrophic production in aquaculture.

FIGURE 5
Concessions group of farms in Southern Chile based upon coordinated actions

Source: Sernapesca. www.sernapesca.cl

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Glossary

Code of Conduct for Responsible Fisheries. FAO-formulated code, which sets out principles and international standards of behaviour for responsible aquaculture and fisheries practices with a view to ensuring the effective conservation, management and development of living aquatic resources, with due respect for the ecosystem and biodiversity.

DEPOMOD. A particle tracking model used for predicting the sinking and resuspension flux of particulate waste material (and special components such as medicines) from fish farms and the benthic community impact of that flux.g

Ecosystem. An organizational unit consisting of an aggregation of plants, animals (including humans) and micro-organisms, along with the non-living components of the environment.

Ecosystem approach to aquaculture. The ecosystem approach to aquaculture is a strategic approach to development and management of the sector aiming to integrate aquaculture within the wider ecosystem such that it promotes sustainability of interlinked social-ecological systems. This is essentially applying an ecosystem based management as proposed by CBD (UNEP/CBD/COP/5/23/ decision V/6, 103–106) to aquaculture and also following Code of Conduct for Responsible Fisheries (CCRF) indications.

Fuzzy classification. Any method for classifying data that allows attributes to apply to objects by membership values, so that an object may be considered a partial member of a class. Class membership is usually defined on a continuous scale from zero to one, where zero is no membership and one is full membership. Fuzzy classification may also be applied to geographic objects themselves, so that an object's boundary is treated as a gradated area rather than an exact line. In GIS, fuzzy classification has been used in the analysis of soil, vegetation, and other phenomena that tend to change gradually in their physical composition and for which attributes are often partly qualitative in nature.

Geographic Information System (GIS). An integrated collection of computer software and data used to view and manage information about geographic places, analyze spatial relationships, and model spatial processes. A GIS provides a framework for gathering and organizing spatial data and related information so that it can be displayed and analyzed.

Global Positioning System (GPS). A system of radio-emitting and -receiving satellites used for determining positions on the earth. The orbiting satellites transmit signals that allow a GPS receiver anywhere on earth to calculate its own location through trilateration. Developed and operated by the United States of America Department of Defense, the system is used in navigation, mapping, surveying, and other applications in which precise positioning is necessary.

Landsat. A series of US polar orbiting satellites, first launched in 1972 by NASA (National Aeronautics and Space Administration), which carry both the multispectral scanner and thematic mapper sensors.

Mariculture. Cultivation, management and harvesting of marine organisms in their natural habitat or in specially constructed rearing units, e.g. ponds, cages, pens, enclosures or tanks. For the purpose of FAO statistics, mariculture refers to cultivation of the end product in seawater even though earlier stages in the life cycle of the concerned aquatic organisms may be cultured in brackish water or freshwater.

Modelling. The representation of a system by a mathematical analogue, obeying certain specified conditions, whose behaviour is used to simulate and interpret a physical or biological system.

Multi-Criteria Evaluation (MCE). Decision support tool for Multi-Criteria Evaluation. A decision is a choice between alternatives (such as alternative actions, land allocations, etc.). The basis for a decision is known as a criterion. In a Multi-Criteria Evaluation, an attempt is made to combine a set of criteria to achieve a single composite basis for a decision according to a specific objective. For example, a decision may need to be made about what areas are the most suitable for industrial development. Criteria might include proximity to roads, slope gradient, exclusion of reserved lands, and so on. Through a Multi-Criteria Evaluation, these criteria images representing suitability may be combined to form a single suitability map from which the final choice will be made.

Remote sensing. Collecting and interpreting information about the environment and the surface of the earth from a distance, primarily by sensing radiation that is naturally emitted or reflected by the earth's surface or from the atmosphere, or by sensing signals transmitted from a device and reflected back to it. Examples of remote-sensing methods include aerial photography, radar, and satellite imaging.

Resolution. The detail with which a map depicts the location and shape of geographic features. The larger the map scale, the higher the possible resolution. As scale decreases, resolution diminishes. The dimensions represented by each cell or pixel in a raster.

Stakeholder. Any person or group with a legitimate interest in the conservation and management of the resources being managed. Generally speaking, the categories of interested parties will often be the same for many fisheries, and should include contrasting interests: commercial/recreational, conservation/exploitation, artisanal/industrial, fisher/buyer-processor-trader as well as governments (local/state/national). The public, the consumers and the scientists could also be considered as interested parties in some circumstances.

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Group photo of selected participants[1]

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FAO FISHERIES AND AQUACULTURE PROCEEDINGS 21

Site selection and carrying capacities for inland and coastal aquaculture

FAO/Institute of Aquaculture, University of Stirling, Expert Workshop
6–8 December 2010
Stirling, the United Kingdom of Great Britain and Northern Ireland

This publication is the proceedings of the Food and Agriculture Organization of the United Nations (FAO) Expert Workshop on Site Selection and Carrying Capacities for Inland and Coastal Aquaculture convened at the Institute of Aquaculture, University of Stirling, the United Kingdom of Great Britain and Northern Ireland, from 6–8 December 2010.

The main purpose of this document is to summarize knowledge and provide guidance to member countries on the process of aquaculture site selection and carrying capacity estimates within an ecosystem approach to aquaculture (EAA). Seven global reviews and ten regional reviews on site selection and carrying capacity encompassing inland aquaculture and coastal aquaculture were presented and discussed at the workshop. Four carrying capacity categories, appropriate for different types of aquaculture, were discussed and agreed upon: physical, production, ecological and social. The range and capability of modelling tools, including spatial tools, available for addressing these capacities were discussed.

The prioritization and sequence for addressing site selection and the different categories of carrying capacity were considered in detail in terms of both regional or national priorities and site-specific considerations.

Two major outcomes have been developed from the workshop: (i) a comprehensive record of the workshop proceedings (this document), which includes global and regional reviews and a summary of major findings and recommendations; and (ii) a set of guidelines for addressing site selection and carrying capacity in the context of the framework of the ecosystem approach to aquaculture (EAA), including summaries of the key findings and recommendations for aquaculture site selection and carrying capacity with an EAA perspective. Recommendations were made for promotion of these concepts and approaches by FAO.

This publication is organized in two parts. One part contains the workshop report and the first global review entitled "Carrying capacities and site selection within the ecosystem approach to aquaculture", while the second part is the full document.

The latter part is available on a CD–ROM accompanying the printed part of this publication.