Progressing aquaculture through virtual technology and decision-support tools for novel management

Expert Panel Review 5.3

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Abstract

Attention is presently turning to the processes, methods and tools that allow the principles of the ecosystem approach to aquaculture to be translated into practical implementation. An essential element for this is the use of virtual technology and decision-support tools, particularly if developing nations are to implement the key elements of aquaculture sustainability. We provide an overview of current and emerging issues and trends related to this topic over the past decade, an assessment of progress with regard to the expectations and commitments expressed in the Bangkok Declaration and conclude with some thoughts for the future.

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Virtual technology is the means by which conceptual models can be made more formal and tested against reality. It involves the collection of data, the integration of these data within a system (information system), the formalization of the system and the action on the system (simulation) with a given purpose. In this review, we therefore address two different types of tools: (a) 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, and (b) tools which allow measurements to be made and translate data into information (information and communications technology).

Natural resource managers, aquaculturists and other stakeholders, pose questions on water quality diagnosis, growth and system carrying capacity and environmental effects, local-scale interactions, prediction of harmful algal blooms, disease control systems, environmental product certification, socio-economic optimization, spatial definition of natural and human components of ecosystems and of competing, conflicting and complementary uses of land and water. Many of these can be addressed, at least in part, by means of virtual technologies and decision-support tools.

The data needed for management and decision-making are similar across most aquaculture operations. However, the space and time resolution of the data sets are dependent on the scale of the aquaculture operation, and depend also on whether it is a single managed entity or an aggregation of independently managed entities. Consequently, the data acquisition approaches and needs expand with the scale of the aquaculture operation, and become a system-scale requirement when placed in the context of spatial planning, ecosystem-scale carrying capacity assessment, and integrated coastal zone management (ICZM).

Examples of key applications focusing on specific issues are provided, and contextualized by means of case studies, addressing a range of culture types and cultivated species; these consider aquaculture sustainability at both the system-scale and farm-scale, deal with open water and land-based pond culture, and with forecasting at the scale of the cultivation cycle and real-time evaluation of animal welfare.

The main constraints in the application of virtual technology in developing countries are identified, together with potential ways to address such problems. Virtual technology and decision-support tools will play an important role in addressing many elements of the *Bangkok Declaration and Strategy*. Some of the directions and challenges are: innovations that will drive virtual technology, information exchange and networking, links between industry and research centers, collaboration between developed and developing countries, strategic alliances in developing countries, and making virtual technology tools more production and management-oriented. Even if attractive and promising, these

tools will have to be adapted to local realities and conditions to really become useful (and used) in the future. This requires a compromise with respect to ease of use, data requirements and scientific complexity. A few of the gaps identified in this review are: disease and harmful algal bloom modelling, use of models for certification and traceability, and modelling with data scarcity.

In the future, virtual technologies will play an increasingly important role in the planning of potential aquaculture siting and production, environmental impacts and sustainability. The next decade will bring about major breakthroughs in key areas such as disease-related modelling, and witness a much broader use of virtual technology for improving and promoting sustainable aquaculture in many parts of the world.

KEY WORDS: *Aquaculture, Decision-support, Geographic information systems, Internet, Management, Models, Remote sensing, Virtual technology.*

Introduction

Background

Attention is presently turning to the processes, methods and tools that allow the ecosystem approach to aquaculture (EAA) principles[1] to be translated into practice. The EAA is the current framework being implemented by the Food and Agriculture Organization of the United Nations (FAO) and is defined as a strategy for the integration of aquaculture within the wider ecosystem in such a way that it promotes sustainable development, equity and resilience of interlinked social and ecological systems (Soto, Aguilar-Manjarrez and Hishamunda, 2008; FAO, 2010).

The implementation of EAA requires the use of a range of methodologies and tools, including environmental impact assessment (EIA) and risk analysis. An essential element for the implementation of EAA will be the use of virtual technology and decision-support tools, particularly if developing nations are to promote the key elements of sustainability and environmental balance as they increase healthy food supply and food security for the population by means of aquaculture.

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[1] The FAO proceedings *Building an Ecosystem Approach to Aquaculture* present the output of an expert workshop organized by FAO and the Universitat de les Balears from 7–11 May 2007 in Palma de Mallorca, Spain. It includes contributed papers on definitions, principles, scales and management measures, human dimensions, economic implications and legal implications that are relevant for an ecosystem-based management in aquaculture. The workshop participants agreed that the EAA should be guided by three main principles that should ensure the contribution of aquaculture to sustainable development: i) aquaculture should be developed in the context of ecosystem functions and services with no degradation of these beyond their resilience capacity; ii) aquaculture should improve human wellbeing and equity for all relevant stakeholders; and iii) aquaculture should be developed in the context of (and integrated to) other relevant sectors (Soto, Aguilar-Manjarrez and Hishamunda, 2008).

Like any economic activity based on finite natural resources, aquaculture is sustainable if its limits in terms of social and environmental costs can be determined, and that information applied for financial return drove development in aquaculture (35 years ago). There was little knowledge or consideration of negative environmental or other impacts in many areas. Large-scale destruction of mangrove habitat in shrimp farming was commonplace, while severe benthic enrichment under salmon cages was another widespread consequence (FAO, 2009). The pace of development, inadequate regulation, and lack of field data and management approaches led to the lingering negative impression of aquaculture that persists today in many areas. Public awareness of the term sustainability has allowed it to enter into common lexicon as a synonym for "environmentally aware", a total simplification of its meaning. Notwithstanding, the term sustainability is difficult to define because it has so many dimensions, including culture, recreation, economics and ecology. In the broadest context of all of these criteria, a general definition of environmental sustainability would be that ecosystem goods and services are not compromised by a given activity.[2]

Issues of sustainability in aquaculture require a consideration of goals and endpoints (i.e. criteria for acceptable impacts), as well as rigorous tools to define these categories. There is diversity in these endpoints, including both economic (e.g. acceptable product size, quality, cost) and ecological (e.g. organic enrichment) criteria. These issues are tied into spatial scales; such scales can be defined, in engineering terminology, as near-field, i.e. in the vicinity of a production site, or far-field, i.e. a broader area, several kilometers from a farm. For example, reduced product quality from overcrowded stocking is an issue more restricted to the area of the farm. Likewise, tourism is not compromised at large distances from farm locations. However, ecological sustainability is linked to the far-field, a typically poorly understood aspect of aquaculture impacts. Research in this area is receiving increasing attention, particularly due to risk of farmed salmon impacts on wild stocks. Far-field impacts on aquaculture farms, such as the offshore development of harmful algal blooms (HAB) and advection to cultivation areas are an additional consideration with both economic and public health effects.

At such broader spatial scales, one is then faced with answering questions about assimilative capacity and indicators of ecosystem health. For this reason, sustainability is closely associated with concepts of ecosystem-based management (EBM) and EAA. The real value of assigning metrics to evaluate indicators exists both in managing existing culture and in the development of new ventures. The guiding principle is that sustainability is easier to plan than it is to retrofit. In this case, retrospective analysis using models is invaluable, and its inclusion in a decision support system imperative.

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[2] See also FAO standard definition of environmental sustainability: according to Brugère *et al.* (2009) Environmental concerns oblige aquaculture policy-makers to assess environmental risks in their planning.

Despite a rather loose framework, the following questions can be posed:

- What is the role of ecosystem modelling in predicting the development of sustainable aquaculture projects?
- How can sustainability be delivered as “advice” to regulators and/or coastal communities?
- What is the scope of solutions to be gained from culture practices such as Integrated Multi-Trophic Aquaculture (IMTA) versus technological advances (e.g. monitoring)?
- How can the specifics of aquaculture be integrated into tools for the assessment of broader coastal sustainability?

Throughout this review, these questions are kept in mind whenever possible, particularly with respect to the choice of case studies illustrating the application of virtual technology.

Review objectives

The Bangkok Declaration (NACA/FAO, 2000) aims to ensure the sustainable development of aquaculture over a ten-year horizon. It is clear that virtual technologies and decision-support tools are directly related to a number of strategic elements referred to in the declaration, such as: applying innovations in aquaculture; investing in research and development; and improving information flow and communication.

We provide an overview of current and emerging issues and trends about virtual technology over the past decade, an assessment of progress with regard to the expectations and commitments expressed in the Bangkok Declaration and conclude with some thoughts for the future.

This thematic review focuses on the following topics:

- *sustainable development of aquaculture*, both in qualitative and quantitative terms – indices of sustainability provide metrics which may be goal-functions of virtual management tools;
- *data acquisition and its relationship with the virtual world* – virtual technologies are of little use without robust underlying data;
- *types and objectives of virtual technology* – focusing on the technologies and what they can and cannot solve;
- *the path from technology to decision-support tools* – with real-world examples of outputs and outcomes; and
- *novel management approaches* – which leverage existing virtual technologies and tools to improve the socio-economic and ecological impacts of aquaculture.

Note: The impact of aquaculture on the environment is mixed, with aquaculture offering relief to overexploited fish stocks while causing long-lasting changes and detrimental impacts on the environment.

Virtual technology and decision-support tools

Definitions and characteristics of virtual technology and decision-support tools

Virtual technology has a fuzzy definition based on the representation of real-life systems by modern technologies. The closest definition can be found in Wikipedia for "Virtual Reality" – a technology which allows a user to interact with a computer-simulated environment, whether that environment is a simulation of the real world or an imaginary world. Therefore, all technologies which allow the construction of an artificial representation of the world and a "player" to interact with this artificial world fall within the definition of virtual technology.

Virtual technology – definition and scope

For the purpose of this review, virtual technology is defined as any artificial representation of ecosystems including the human element as recommended by the Ecosystem Approaches (EAs). Such representations, exemplified by mathematical models, are designed to help map, measure, understand, and predict the underlying variables and processes, in order to inform an ecosystem approach to aquaculture (EAA).

Representation of reality coincides with the modelling vocabulary. Models can be a conceptual view of the world which depends on culture, language, senses (sight, hearing, etc.), and are always a simplification of reality that is built with a given purpose. All models seek to optimize a trade-off among generality, realism, accuracy and simplicity.

Virtual technology is thus the means by which conceptual models can be made more formal and tested against reality. It involves the collection of data, the integration of these data within a system (information system), the formalization of the system and the action on the system (simulation) with a given purpose. We will therefore distinguish between two different types of tools, both of which are addressed in this review:

- tools which allow measurements to be made and translate data into information (information and communications technology, ICT); and
- 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.

Since virtual technology is typically driven by one or more specific objectives, we will review the existing applications of virtual technology in the field of management of living resources (which directly links to aquaculture), with a focus on the specific issues addressed.

Stakeholder groups

We focus on the key questions asked by natural resource managers, aquaculturists and other stakeholders, and contextualize these with respect to virtual technologies and decision-support tools. These questions include water quality diagnosis, growth and system carrying capacity and environmental effects, local-scale interactions, prediction of harmful algal blooms, disease control systems, environmental product certification, socio-economic optimization, spatial definition of natural and human components of ecosystems and of competing, conflicting and complementary uses of land and water.

Different stakeholders respond to these questions at differing time and space scales; for instance, an environmental manager for an estuary or coastal bay might be interested in system-scale carrying capacity, both in terms of production and environmental impact, while at the level of integrated coastal zone management (ICZM), the role of bottom-up (e.g. nutrient-related) effects and top-down (e.g. shellfish grazing) control might be an important consideration. Farmers will be more concerned with optimizing production and profit, disease control and market acceptance. Farmers and managers in the west may be more focused on open coastal systems, whereas in Asia, Central and South America, or in Africa substantial emphasis is placed on inland or fringing systems such as shrimp and/or fish pond culture.

An important third group of stakeholders are coastal residents and community groups. When they are engaged in scientific endeavours, it is beneficial to the entire process. In particular, communities are empowered to enter the decision process, especially when involved in the data collection aspects. Moreover, they have an inherent interest in the broader spatial scale, being concerned about more than just the local areas of aquaculture activity. In this context it is worth noting that there are key cultural differences in community approaches to coastline use; for instance in many areas of the United States of America and Europe, shorefront use is seen as primarily recreational, whereas in many parts of Asia there is a more utilitarian approach with respect to multiple uses, including cultivation of marine species.

Major issues and trends during the past decade

The recent literature shows a marked increase in the number of papers (from 300 in the 1990s to 1 400 in 2009) dealing with the management of aquaculture, based on a keyword search for “aquaculture” and “management” on http://sciencedirect.com.

The response of the academic community was driven by the rapid increase in aquaculture activities in the last ten years, which in turn has generated and/or increased the public awareness of the environmental impact of aquaculture and emphasized the risks of improperly managed aquaculture products to human health. Still, there is much public ignorance on aquaculture impact. Irrespective of whether inaccurate information is generated deliberately to promote a specific cause or inadvertently through ignorance, it can have a major impact on public opinion and policy-making.

Even though it is very difficult to identify general trends, concerns about environmental consequences and competition for resources, such as the "fishmeal trap", have led to:

- complex site selection protocols, based on an integrated assessment which includes the estimation of assimilative capacity of environment, for finfish, and of carrying capacity, for shellfish, as well as the potential benefits and disadvantages due to conflict of uses with other activities such as fisheries, tourism and navigation, in particular for nearshore sites;
- management practices which tend to minimize emission of organic matter;
- feeding regimes which minimize use of trash fish, fish oil and fishmeal in feed by substitution from terrestrial sources;
- concern, at least within the salmon industry, on interaction with/impact on wild stocks. "Escape security" is a major issue in farm-scale management in order to reduce the risk of genetic impact from farmed salmon;
- impact of exotics imported for cultivation on the distribution of native species (e.g. the spread of the giant cupped oyster (*Crassostrea gigas*) in the Zeeland area of the southern Netherlands). This takes on particular importance in the light of climate change, due to biogeographical shifts in reproductive limits;
- design and application of monitoring programmes aimed at ensuring both compliance with environmental legislation and optimization of husbandry operations; and
- adoption of marketing strategies and market-led environmental management based on product traceability and ecolabelling.

In mature industries, such as salmon culture, these changes, which bring about additional costs, are causing a shift from independent medium-scale fish farms to multinational mariculture enterprises (Grøttum and Beveridge, 2007), which can successfully compete by reducing the costs through economies of scale, increasing the size and efficiency of production units. This trend is likely to be followed by other emerging aquaculture industries, as long as the sectors grow and the competition intensifies.

Several papers (e.g. Soto *et al*., 2008) emphasize the role of spatial scales in aquaculture, but it should be noted that the distinction between feed-based and organic extractive cultures is important for identifying the set of virtual management tools which might best be applied, because the set of environmental services required is markedly different in the two cases.

Virtual technologies are already playing a major role in the transition of aquaculture towards a mature industry, as illustrated in our section on case studies, and their importance is likely to increase with the further development of IMTA, which is regarded as a promising means of enhancing sustainability and efficiency, in particular of cage culture (Tacon and Halwart, 2007).

Aquaculture management

Aquaculture management can be viewed from various perspectives (Ferreira *et al*., 2008a), including: (i) insertion within the context of ICZM; (ii) the regulatory approach for granting licenses at the ecosystem scale; (iii) licensing of individual farms and monitoring of activities; and (iv) farm-scale management by the operators. In all of these cases, virtual technologies have an important role to play, be it through the use of (i) geographic information systems (GIS), remote sensing and ecosystem-scale models to determine suitability and carrying capacity; (ii) farm-scale tools to support licensing, environmental impact assessment (EIA) and optimization of production; or (iii) sensors for data acquisition for monitoring and modelling.

Marine spatial planning is another area where aquaculture management and virtual technology interact, through the use of GIS and other tools for harmonizing multiple uses of marine ecosystems. Aquaculture management can greatly profit from an ecosystem-based approach, combining scales and issues to promote sustainable activities. In itself, this kind of ecosystem approach is essential for ICZM, which forms the paradigm for water management in many parts of the world (e.g. Hovik and Stokke, 2007; Borja *et al*., 2008; Nobre and Ferreira, 2009). European examples include the River Basin Management Plans required by the European Union (EU) Water Framework Directive (WFD) (EC, 2000), the holistic combination of descriptors, including e.g. biodiversity, sea floor integrity, food webs and eutrophication in the EU Marine Strategy Framework Directive (MSFD) (EC, 2008), and the impact model of five environmental aspects in the Strategy for an Environmentally Sustainable Norwegian Aquaculture Industry from the Norwegian Ministry of Fisheries and Coastal Affairs (2009).

Figure 1 illustrates an example of a decision support system titled MarGIS™; it is a near real-time interactive software application, tailored specifically for

FIGURE 1

Layout of oyster trestles in Dungarvan Harbour, Ireland, showing a geographic information systems (GIS) overlay, colour-coded for different cohorts of cultivated animals

Source:
Dallaghan (2009).

shellfish growers around the Irish coast, which will enable them to optimize their operations and production in a sustainable and environmentally sensitive manner. By using near real-time current conditions, MarGIS™ will allow a farmer to quickly see what effect on his productivity would be expected if he were to make stocking density changes, for example, or to reposition one or all of his mussel lines, or introduce more mussel lines in the vicinity of the existing farm. By allowing the optimization of husbandry techniques such as this, the software encourages farmers and communities to work together.

Scales

Spatial and temporal changes in the natural and human context raise issues for aquaculture (e.g. impacts on the environment, social and economic changes) but also provide frameworks for problem solving once the scale issues have been defined. EAA, the current framework being implemented by the FAO (Soto, Aguilar-Manjarrez and Hishamunda, 2008; FAO, 2010), provides guidelines for integrating aquaculture into the natural and human environments as well as for defining future goals for aquaculture development and management.

The objective of this section is to summarize experience in applying GIS, remote sensing and mapping to spatial and temporal issues in aquaculture. The geographic perspective is global. The material comes mainly from a review on spatial tools, decision-making and modelling in aquaculture by Kapetsky, Aguilar-Manjarrez and Soto (2010).

Spatial scales

Experts at the FAO Workshop on "Building an Ecosystem Approach to Aquaculture" (Soto, Aguilar-Manjarrez and Hishamunda, 2008) identified three scales/levels of EAA application: the farm, the waterbody and the global market-trade scale. Detailed definitions and examples of the EAA scales are now available as general guidelines (FAO, 2010).

Preceding the development of the EAA scales and based on the GISFish Aquaculture Database (www.fao.org/fishery/gisfish), Kapetsky, Aguilar-Manjarrez and Soto (2010) classified GIS applications according to stated or implicit scales among inland, brackishwater and marine environments. Seven scales were recognized among 159 applications in these environments, based on administrative divisions (i.e. local, state/province, region, country, multicountry region, continental, global).

Although one could consider spatial scales over a wide range, in the context of virtual technologies, it is most useful to address those relevant to potential ecosystem interactions, namely from farm to bay scale. Management decisions made at larger scales such as watersheds better address the EAA and can greatly benefit from the use of GIS tools. These approaches are contained within the broader concepts of marine spatial planning or zoning (Douvere, 2008;

Klein *et al*., 2009). In terms of the EAA scales, GIS applications applied to the farm and the waterbody were among the most numerous. This is unsurprising because most issues and most spatial applications to address them are expected to be at those scales.

Since spatial analyses can be applied at any scale (e.g. EAA, other frameworks), the appropriate scale can be defined by the geographic scope of the problem when expressed in ecosystem, administrative, social and economic terms. Spatial analysis and GIS-based tools principally aim to help us understand combined information at/from different scales, and are in that sense independent of scale. A good example could be an integrated watershed management scheme to combine agriculture, aquaculture and irrigation at different scales and watershed boundaries.

In practice, there is lack of experience using spatial tools in aquaculture when dealing with social scales – stakeholders at all levels – and to a lesser extent with economic scales. This can be addressed to some extent by scenario building with interactive GIS applications such as Marxan (Watts *et al.*, 2009).

Temporal scales

The temporal scales of interest for spatial analyses, like the spatial scales, are those defined by the problem, in this case, the duration of the issue or impact. In addition, the frequency of particular phenomena (e.g. HAB or El Niño) may be a conditioning factor. Three types of temporal scales may be recognized (Table 1).

TABLE 1
Summary of temporal scales of interest for spatial analysis

Temporal scales	Description
Natural	Changes in environment-aquaculture interactions over a range of seconds to millennia, but practically encompassing the economic life of aquaculture as a species-culture system
Socio-economic	The range of time that aquaculture is socially and economically viable, which can range from the earliest planning to the end of the business or programme, years to decades
Administrative	The range of time during which local traditions and/or legislation affects aquaculture, years to decades

Prediction is the objective underlying nearly all spatial analyses. Within the temporal scale of the problem are the limits imposed by the quality and quantity of historical data and the availability or utility of models and decision-support tools. An analysis of temporal scales was not included as part of the Soto, *et al*. (2008) review; however, it can be stated that most studies are "snapshots" in that the results, whether cast in the past, present or future, are for one or a few instances in time, even though they may be based on long series of environmental data. Real-time environmental forecasting in support of daily aquaculture operations is a temporal scale that will become increasingly important, as exemplified in the Welfaremeter case study presented later in this review.

The interaction of spatial and temporal analyses is also important, an obvious application being land-use changes, and the way these affect aspects such as the environmental drivers for aquaculture of bivalve shellfish and seaweeds, which extract their food resources from the natural environment. Changes in spatial patterns through time are fundamental to aquaculture planning and management, e.g. accurate data on distribution and stocking density of various species, incidence of disease and changes in mortality. From a technical standpoint, they may be limited by the quality of spatial data and the availability of time series at specific locations, but the importance of GIS tools for presentation and understanding of scales and interactions cannot be overemphasized.

Data and information

Data and information types

The data that are needed for management and decision-making are similar across most aquaculture operations (Table 2). However, the space and time resolution of the data sets is dependent on the scale of the aquaculture operation and also on whether it is a single managed entity or an aggregation of independently managed entities. Consequently, the data acquisition approaches and needs expand with the scale of the aquaculture operation and become a system-scale requirement when placed in the context of marine spatial planning, ecosystem-scale carrying capacity assessment, ICZM and responsible management of inland capture fisheries resources.

TABLE 2
Thematic data collection for use of virtual tools, applied on scales ranging from individual farm to watershed

Issue	Key variables *
Morphology & climate	Topography, bathymetry, rainfall distribution, air temperature, wind speed, relative humidity
Water availability, inputs & exchange	Volume, seasonal & annual hydrographs, tidal range & prism, current velocities, residence time
Water quality	Temperature, alkalinity/salinity, suspended matter, nutrients, organic detritus (POC or POM), dissolved oxygen, chlorophyll, extent of submerged aquatic vegetation, xenobiotics, microbiology
Environmental interactions	Fouling, pathogens, extent of submerged aquatic vegetation, benthos
Culture practice	Timing of seeding & harvesting, mortality, cultivation density, size range, feeding (in the case of finfish & shrimp)
Socio-economics	Business fundamentals, infrastructure, direct employment, economic multipliers, use of vessels, etc

Terminology: particulate organic carbon (POC); particulate organic matter (POM).

* The most relevant variables are indicated, but as this is a non-exhaustive list it could also include soil type, roads, cities, locations to markets, plant cover, demography, land use patterns, etc.

Acquisition

Water quality data sets are acquired via discrete water samples and automated sampling systems. Automated water quality sampling systems for small and large-scale aquaculture systems have been available for many years (see review in Lee, 1995) and are considered routine measurements. Similarly, freshwater availability and input can be obtained through gauging of rivers and tributaries, and these measurements are routine in many countries. *In situ* data can be readily acquired at the farm scale (whether in a pond, estuary or coastal area of an ocean) by informed placement of sensor and/or mooring arrays which return information on local environmental conditions.

The spatial scale of *in situ* measurements can be expanded to the system scale by use of satellite-derived remotely sensed data (Table 3). Chen, Zhang and Hallikainen (2007) provide an example of combining satellite-derived and *in situ* data sets for water quality monitoring at a scale of a system of river basins. The algorithms used to obtain derived products from satellite observations (Table 3) were developed for open-ocean temperate waters (see Hooker and McClain, 2000), but there are specific algorithms for coastal waters. Images from near the coast may be data-poor, since there are data flags and aspects of atmospheric correction meant to improve data quality for open ocean. However, awareness of these restrictions and careful removal of data flags can lead to greater recovery of ocean colour information close to the coastline (e.g. Hu *et al*., 2004).

To maximize the utility of remote sensing data, which is often a cost-effective approach in information-poor regions, *in situ* data sets should be used to establish and calibrate algorithms for applications to estuarine and nearshore coastal waters where aquaculture systems are likely to be established. In particular, algorithms that allow detection of harmful algal blooms (HABs) are critical to maximizing the production of farm-scale operations because satellite remote sensing is a tool that can potentially provide early detection (and warning) of HAB events. Further, characterization of vegetation and land cover changes in watersheds and coastal environments which affect runoff and discharge to coastal bays and estuaries is possible with satellite-based observations (Table 3) and provides a means for monitoring the effects of aquaculture operations at watershed scales.

Techniques that allow integration and synthesis of satellite and *in situ* data are required for these data to be fully utilized to provide estimates of system-scale carrying capacity. Significant efforts have been made using GIS technology to combine disparate data sets (Nath *et al*., 2000) for natural resource management. These approaches will become more important as the volume and types of data increase and as aquaculture facilities expand.

Frameworks that couple circulation, lower trophic level, shellfish/finfish growth, population and financial and profit models provide another important

TABLE 3
Remote sensing data

Sensor	Data	Example derived data products	Data availability
Very High Resolution Radiometry (AVHRR)	Sea surface temperature	Surface heat flux	http://nsidc.org/data/avhrr
Sea Wide-Field-of-Viewing (SeaWiFS)	Ocean colour, water column light	Turbidity, chlorophyll, primary production, POC, CDOM	http://oceancolor.gsfc.nasa.gov
Moderate Resolution Imaging Spectroradiometer (MODIS)	Ocean colour (chlorophyll), water column light	Turbidity, chlorophyll, primary production, POC, CDOM	http://oceancolor.gsfc.nasa.gov
LandSat Thematic Mapper (TM)	Vegetation & land cover type	Land cover, land use change	http://landsat.gsfc.nasa.gov
Enhanced Thematic Mapper (ETM)	Vegetation & land cover type	Land cover, land use change	http://landsat.gsfc.nasa.gov
LIght Detection And Ranging (LIDAR) systems	Elevation	Biomass measurements, land cover	Various
Compact Airborne Spectrographic Imager (CASI)	Optical properties	Biomass measurements, land cover	Various

Terminology: particulate organic carbon (POC); particulate organic matter (POM); coloured dissolved organic matter (CDOM)

data synthesis and integration tool (e.g. Ferreira *et al*., 2008a,b, 2009). The case studies described later variously use combinations of GIS and coupled modelling frameworks for synthesis and integration of data sets, and the output from this for decision support and management of aquaculture operations. These modelling systems require extensive *in situ* and remotely sensed (e.g. Table 3) data sets for model development and evaluation.

Accurate representation of water circulation is central to estimating production and carrying capacity of aquaculture systems (e.g. Guyondet, Koutitonsky and Roy, 2005). The residence time and exchange of water, variables that are important for aquaculture farm systems, can be estimated from current meter, tidal gauge and drifter measurements. These data can be combined with a three-dimensional hydrodynamic model to estimate flow, exchange and residence time over multiple space and time scales and to undertake scenario testing. The community expertise and knowledge of circulation models is greatly improved and community-based models now exist (e.g. the Regional Ocean Modeling System (ROMS, http://myroms.org); Princeton Ocean Model (POM); the Unstructured Grid Finite Volume Coastal Ocean Model (FVCOM); and the Generalized Environmental Modeling System for Surfacewaters (GEMSS)) that have been applied to a range of environments and have large user communities. Implementation of regional circulation models requires local understanding for model development and environmental data for evaluation of simulations.

Climate simulations provide a valuable data resource for site selection for new aquaculture facilities or for projecting system carrying capacity or long-term production from existing facilities under various climate scenarios. The development of approaches to downscale the output from climate models to regional scales (e.g. Wilby *et al*., 1998; Wood *et al*., 2004; Salon *et al*., 2008; Melaku Canu *et al*., 2010) will allow assessment of potential effects of climate warming on rainfall patterns, precipitation and freshwater fluxes.

Other techniques such as life-cycle analysis, human appropriation of primary productivity and ecological footprint are described in a review on environmental impact assessment (EIA) and monitoring in aquaculture by FAO (2009).

Availability and data sharing

In order to gauge development and management prospects for aquaculture, there is a need to measure impacts imposed on aquaculture from anthropogenic sources and through natural variation in the environment. In turn, it is essential to have an appreciation of the status of ecosystems in which aquaculture resides because aquaculture issues (generally related to environmental, social and economic changes in the context of the EAA) have to be resolved within broader competing, conflicting and complementary uses of land and water. The same is true when evaluating aquaculture's potential impacts on the environment as well as on social and economic systems. For these tasks, spatial data relating to ecosystems and social, economic and administrative realms are required.

As part of a review aimed at evaluating the status of spatial tools, decision-making and modelling to support the implementation of EAA (Kapestsky, Aguilar-Manjarrez and Soto, 2010), an assessment of two broad kinds of spatial data was made: (i) data on large ecosystems already spatially defined; and (ii) spatial data that could be used to define ecosystem boundaries as well as for other uses in aquaculture development and management, both generic (e.g. administrative boundaries) and local (e.g. environmental hotspots). The following conclusions were reached on the availability and gaps in spatial data:

- Examples in aquaculture of the use of environmental data (relating to EAA Principle 1, ecosystem functions) are common. In contrast, examples of the use of social and economic spatial data (relating to EAA Principle 2 on human well-being and equity), and spatial data used to assess other sectors, policies and goals (EAA Principle 3) are much less common. However, this is not necessarily due to lack of data. Rather it could be because of a lack of impetus to use it and perhaps a more generic failure to employ the multidisciplinary approach (natural/social/economic) required by the EAA.
- Relatively high-resolution data, such as would be used at the EAA farm and waterbody/aquaculture zone scales, are needed to spatially resolve environmental, social, economic and administrative issues in aquaculture.

- There is a vast amount of mainly low-resolution/large-scale spatial data freely available on the Internet that could be potentially important for aquaculture at the global and regional scales.
- Many of these datasets could also be useful at the national and subnational levels, but considerable effort will be required: (i) to find the data and then; (ii) to determine the quality and applicability of the spatial data relative to the appropriate resolution, spatial and temporal coverage.
- The demand for spatial data is already greatest where most of aquaculture's social, economic and environmental issues are focused, namely at the farm, watershed/waterbody and aquaculture zone scales of the EAA, but such data are likely to be less readily available in developing countries; this may be compounded by a lower regulatory capacity.

Bundy *et al.* (2009) recently reviewed the issue of data sharing with respect to remote sensing products and identified a number of promising avenues for this purpose, including interdisciplinary working groups, Web-based portals which simplify product access (e.g. www.borstad.com/grip.html), and capacity-building networks such as ChloroGIN (http://chlorogin.org) and MyOcean (http://myocean.eu).

Available tools

Role of tools

Virtual technology includes a number of techniques that have emerged over the past decades, such as data objects for storage, processing and representation; GIS; and simulation models of various types (Table 4). The common link among these is their abstraction of physical (real) systems, either because they provide an image of that reality, which can be layered and manipulated, and/or because they can be used to predict a state change on the basis of real or scenario-based forcing. In combination, these technologies constitute a powerful arsenal that can be molded into instruments appropriate for decision-makers.

TABLE 4
Virtual technology: objectives, scales, and example applications and tools

Objective and issues	Technology	Scale	Applications
Control production			
Control the production process	Information technology, automatic sensors, etc.	Microscale (farm)	Use of information technology in aquaculture (Bostock, 2009)
Optimize production			
Define the best set of production parameters with respect to environmental, economic & social benefits	Mathematical models	From microscale (farm) to mesoscale (ecosystem/ social/ economic)	The FARM Aquaculture Resource model (FARM) (Ferreira, Hawkins and Bricker, 2007)
Map resources & environment, spatial & temporal indicators			
Evaluate the potential for exploitation of living resources, taking into account ecological services & human activities, as well as environmental changes & risks for aquaculture	GIS, remote sensing	From mesoscale (ecosystem) to micro-scale (farm)	Remote sensing in fisheries & aquaculture (IOCCG, 2009)

TABLE 4 (Continued)

Objective and issues	Technology	Scale	Applications
Risk assessment			
Evaluate the environmental risk posed by aquaculture activity, in order to improve management, define best practices & define monitoring plans	Risk assessment handbook, mathematical models, expert knowledge, literature review, monitoring	From micro (local) to macroscale (transboundary)	Understanding & applying risk analysis in aquaculture (Bondad-Reantaso, Arthur and Subasinghe, 2008)
Build indicators of sustainability			
Evaluate the sustainability of resource management by taking into account the social, economic & ecosystem concerns	Stakeholder fora; enquiries; database regarding economic, social & environmental indicators; life cycle assessment (LCA)	Mesoscale (economic sector)	- Environmental analysis of the Norwegian fishery & aquaculture industry (Ellingsen, Olaussen and Utne, 2009) - Assessment of sustainable development of aquaculture (Aubin, 2008) - Consensus project to bring together stakeholders to measure the path towards sustainable aquaculture in Europe (http://euraquaculture.info)
Assess system changes			
Allow adaptation to changes due to other human activities or environment	System approach, mathematical models	From meso- (regional) to macroscale (national, transboundary), social/economic/ecosystem integration	An integrated modelling approach for the management of clam farming in coastal lagoons (Marinov *et al.*, 2007)
Communication and learning			
Improve/increase social acceptance of aquaculture, scientific & technical knowledge, political awareness, stimulate innovation, etc.	Web-based technologies, e-learning, social fora, technical networks, demonstration tools	From meso- (regional) to macroscale (national, transboundary)	Use of information technology in aquaculture (Bostock, 2009) European Thematic Network in aquaculture, fisheries and aquatic resources management (AQUA-TNET) (www.aquatnet.com/index.php/26/about-aqua-tnet)

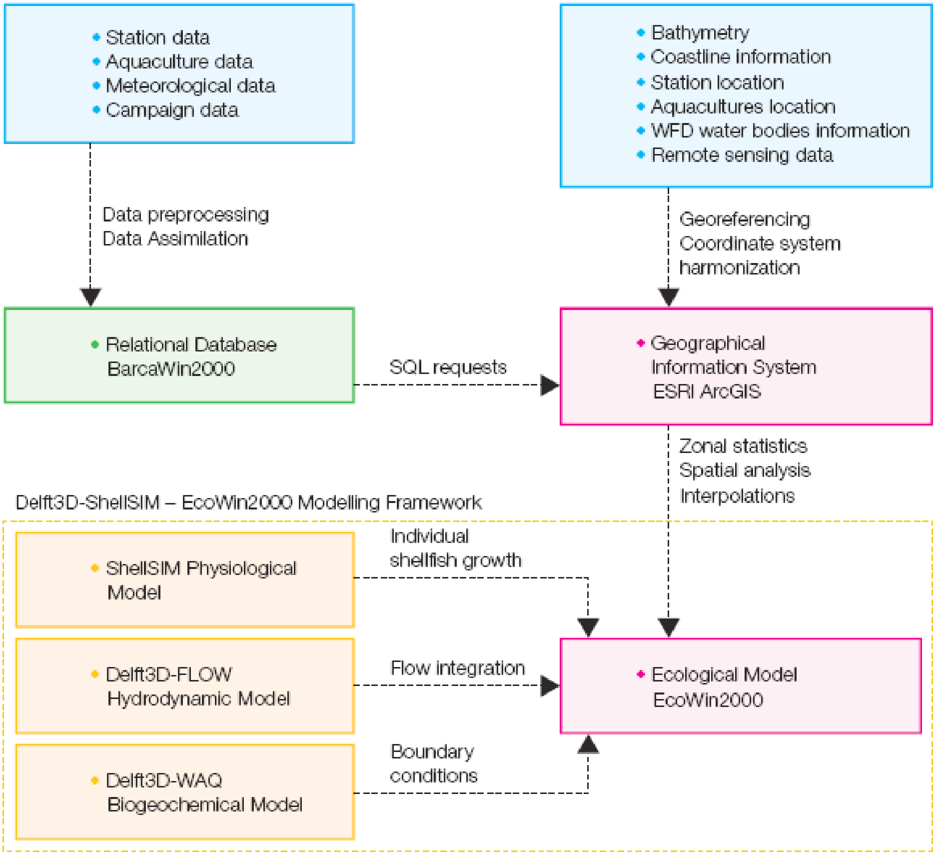
Types of tools

Figure 2 provides an example of how a range of tools can be combined for system-scale aquaculture management. The upper part of the figure deals with the requirements for data and the tools used to process discrete water samples, spatial (e.g. bathymetry) and socio-economic (e.g. aquaculture, legislation) data into information that can be used in models, for input, validation, constraint management and scenario development.

The lower part of Figure 2 shows how modelling tools working at different time, space and functional scales (individual shellfish growth models, system-scale detailed circulation models, coarser grid ecological models for decadal simulations) can be combined into a decision support system. In this case, the system is distributed, allowing stand-alone use of the various tools.

In the Sustainable Options for People, Catchment and Aquatic Resources (SPEAR) project (Ferreira *et al*., 2008a; http://biaoqiang.org), this approach has been further extended with the incorporation of catchment modelling by means of the Soil and Water Assessment Tool (SWAT, Nobre *et al*., 2010). This addition allows managers to explicitly couple watershed uses and their influence on coastal discharges with aquaculture yields and ecosystem impacts.

FIGURE 2
Interactions between different tools used in the SMILE project, (www.ecowin.org/smile)



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

Tools can be developed for mandatory regulation purposes, and integrated for decision support in management systems. The MOM (Modelling-On growing-Monitoring) system (Ervik *et al*., 1997) is developed and mandatory by regulation in Norway, for monitoring the effects on the bottom and on benthic fauna under and near farming facilities. The methods describe how effects on the seabed are to be monitored, and which limit values (environmental standards) are to be applied to assess whether such effects are acceptable. Based partly on the MOM system, an integrated management system MOLO (environmental monitoring – location) has recently been launched to regulate a broader scale of environmental effects and area adaptation in aquaculture. Localization will be a central feature of the new system for zoning and environmental adaptation. Part of this will involve guidelines for coastal zone management planning for aquaculture areas regulated by the Norwegian Planning and Building Act.

In Scotland, DEPOMOD is used in regulating salmon farm maximum biomass and also for consenting the discharge of infeed sealice medicines. DEPOMOD couples a particle tracking model (of waste feed and faeces) and an empirical benthic response model to yield predictions of benthic impact based on environmental parameters (e.g. bathymetry, depth, currents) and farm management (e.g. cage layout, feed inputs) (Cromey, Nickell, and Black, 2002; Cromey *et al*., 2002).

Novel management

Overview

A brief overview is provided below of how virtual tools can address the specificities of different types of aquaculture, providing novel approaches to management by means of the application of models of different types. Such models may be used as a stand-alone resource, combined in order to take advantage of complementary strengths, and leveraged by means of remote sensing and other technologies. The issues vary depending on whether the cultivation is intensive or extensive, on the type of food source (i.e. feed, organic extraction, inorganic extraction), and on the combination of species used. The first section focuses on feed-based culture, the second on bivalve shellfish, and the final part on IMTA.

Feed-based (cage aquaculture, pond)

At present, virtual management tools for feed-based culture are focused primarily on site selection and assessment of sustainable production, based on the holding capacity of the environment (cage culture) and on the minimization of waste waters (pond culture). Some studies also present the development of decision support systems (DSS), which could help farmers in selecting sites, species and, to a certain extent, provide guidelines for management practices. The MOLO system in Norway is currently under development, and includes (i) AkvaVis (see Case study 3); (ii) integration of hydrodynamic modelling, welfare and production in salmon pens; (iii) food availability to mussels; (iv) wave exposure;

and (v) risk of disease. This is one example of new integrated/comprehensive management systems, although as yet not implemented in management. Such tools may also include an economic component, thus allowing users to estimate profit (Halide *et al*., 2009) and in some instances, optimization techniques may also be incorporated (Bolte, Nath and Ernst, 2000).

However, these examples are still relatively rare, and a comprehensive, systemic approach to the optimization of management practices is still lacking, in particular in cage culture. Furthermore, most models and DSS developed in the last decade do not provide quantitative sustainability assessment in the form of holistic indicators, based on matter and energy budgets. Some examples of application of this class of indicators to "mature" aquaculture productions are emerging in the literature: Martinez-Cordero and Leung (2004) proposed environmentally adjusted production indicators for assessing the sustainability of shrimp farming in Mexico; D'Orbcastel, Blancheto and Aubin (2009) compared the sustainability of two trout farming systems by means of life cycle assessment (LCA) analysis. These tools and indicators could be helpful both for identifying inefficiencies and providing the basis for ecolabelling aquaculture products, thus increasing their social acceptability and, potentially, the profit of those farmers who follow more sustainable practices.

Another area of improvement is represented by the development of management tools based on the combination of mechanistic and statistical models, which would help decision-makers to take into account the often large uncertainty in both environmental and economic drivers that cannot be controlled by farmers. In this context, risk analysis may be a viable approach (Soto *et al*., 2008; GESAMP, 2008), but existing tools could also be improved by adding global sensitivity and uncertainty modules, which could allow uncertainty estimates in the relevant outputs (biomass yield, expected revenues, etc.) with respect to uncertainty in the drivers and model parameters. This change may also lead to the selection of different "optimal" practices, since sometimes "optimal" solutions found by linear programming tools are not robust in respect to fluctuations in the input data.

Lastly, existing tools may not be entirely suitable for the implementation of "adaptive management", which is regarded as a desirable practice in EBM, since they often rely on "static" data archives. In this context, the World Wide Web should probably be taken into consideration as a potential delivery medium for real-time data concerning non-manageable drivers, such as the occurrence of HABs or acute water pollution events, weather and market prices, on which short-term prediction could be based. Dedicated Web sites can either allow direct access to these data or provide appropriate links. These data could be combined with high-frequency site-specific data concerning the evolution of key water quality variables within ponds/cages and models, as is described in the welfaremeter case study (Case study 6) presented below.

Shellfish farming

Shellfish production relies heavily on the resources provided by the environment (unpolluted waters, adequate trophic resources, in many instances seed) and requires the allocation of rather large areas within coastal waterbodies. Therefore, on the one hand, the set of “control variables” which can actually be managed by a farmer is reduced, in comparison with feed-based aquaculture and, on the other, the separation between the farm scale and the regional scale is less sharp, in particular in semi-enclosed embayments and lagoons. In these environments, the competition for resources among farmers, who may also be part-time fishermen, may be high, and in many cases is mitigated by the formation of cooperatives which collectively manage a certain number of farms.

The estimation of the production and/or environmental carrying capacity at a water basin/regional scale is still the focus of the majority of studies concerning the assessment of the environmental sustainability of shellfish farming. These studies do not in most cases address economic sustainability. Recently, a more comprehensive approach, based on a dynamic ecological-economic model, was proposed (Nobre *et al*., 2009), taking into consideration to some extent the within-region variability. Another example of ongoing research is the EU Science and Policy Integration for Coastal System Assessment (SPICOSA) project (www.spicosa.eu), where partners are trying to model interlinks among ecology and socio-economics at several study sites.

These types of approach should be further developed and coupled with GIS, which, in general, could provide a suitable platform for including other constraints related to conflicts of use and water quality issues. For example, assessment of the contamination of shellfish by heavy metals and organic toxicants is not usually taken into consideration, but could be taken into account by coupling individual/population dynamics models with simple bioaccumulation models. Such models could also point to critical or subcritical situations, thus setting the scene for cost-effective monitoring. An emphasis on shellfish welfare and food security, which could be achieved through monitoring, proper certification and traceability, would improve consumer acceptance and potentially increase both revenue and profit. Therefore, estimation of the uncertainty in the biomass yield and adaptation of the above strategies in relation to short-term prediction are even more crucial for maximizing profits or minimizing losses due to adverse events. Among those, HABs certainly represent one of the major problems. Early warning and short-term prediction of the dynamics of HABs, based on the integration of real-time monitoring and operational hydrodynamic models, would certainly improve the capability of mitigating the adverse effects of HABs. Shellfish farms are often closed following rains due to land-based pollution (Conte, 2007); monitoring and modelling based on virtual technologies would seem to be an excellent way to address this.

Integrated Multi-Trophic Aquaculture

IMTA is indicated as one of the main paths towards sustainable aquaculture (Soto, 2009). However, farm-scale applications are still limited, in particular in Europe, perhaps due to the higher costs associated with IMTA and the higher complexity of IMTA farms. Another important element is the identification of markets for successful placement of the full range of IMTA products, which relates both to cultural aspects and to producer awareness (for instance, a finfish farmer may not be aware of commercial opportunities for agar manufacture for co-cultivated seaweeds).

Virtual management tools have a great potential for exploring possible alternatives and assessing the potential benefits if ecological and economic models are integrated; the goal is to provide a realistic estimation of the medium to long-term profitability of IMTA. IMTA began thousands of years ago in the People's Republic of China, and was initially developed by farmers because this approach produced much more output than monoculture for an identical input. In other words, IMTA has the potential of being economically more cost effective; it has a higher average physical product (APP). Although papers on this topic first appeared in western journals several decades ago (Tenore, Goldman and Clarner, 1973; Ryther *et al*., 1975), IMTA is rarely implemented in the west, even though fish farming companies on both coasts of Canada have adopted aspects of IMTA. However, it is widely and extensively used both in China (Li, 2006, collects 17 papers on experimental combinations of cultivated species in IMTA), where it is the traditional form of aquaculture, and in the developing countries of Southeast Asia. The application of IMTA has been mainly driven by economic factors, but more and more interest has been focused in recent years on its significant advantages with respect to environmental sustainability.

Virtual technology such as GIS, remote sensing and modelling has begun to be extensively applied in this traditional industry through international scientific programmes (e.g. the EU SPEAR project: Ferreira *et al*., 2008a). Virtual management tools, particularly models that integrate ecological and economic components (Whitmarsh, Cook and Black, 2006; Nobre *et al*., 2009) will play an important part in the future development of IMTA both locally and globally, and in assessing its role in ICZM.

Case studies

Kapetsky and Aguilar-Manjarrez (2007) and Ross, Handisyde and Nimmo (2009) provide an overview of decision support using GIS tools for aquaculture. Several descriptions of tools have been published in the last decade (e.g. Salam, Khatun and Ali, 2005; Ferreira, Hawkins and Bricker, 2007; Hossain *et al*., 2009; Ferreira *et al*., 2009; Nobre *et al*., 2010), while information on other tools such as AkvaVis is available through the Web. A synthesis of the main objectives, technologies and examples of application is presented in Table 4.

Additional descriptions of several types of aquaculture models together with some theoretical background and evaluation of indicators can be found on www.ecasatoolbox.org.uk.

In this section, seven case studies (Table 5) have been selected for a more detailed review to illustrate the potential of different types of software

TABLE 5
Summary of case studies using virtual tools for different objectives, species, and scales

	Case Study N° 1 PEI	Case Study N° 2 SPEAR	Case Study N° 3 AkvaVis	Case Study N° 4 UISCE MarGIS	Case Study N° 5 FARM	Case Study N° 6 WELFAREMETER	Case Study N° 7 POND
Main management issue(s)	Ecological carrying capacity	Carrying capacity for Integrated Multi-Trophic Aquaculture	GIS for site selection, carrying capacity & management monitoring in aquaculture	GIS & dynamic modelling to support aquaculture management	Prediction of production, economic outputs & environmental effects over the culture cycle	Real-time monitoring of welfare for cultured finfish, coupling real-time data & models for day to day farm management	Production of shrimp farms in pond culture
Stakeholders	Water managers, aquaculturists	Water managers	Water managers, aquaculturists	Water managers, aquaculturists	Water managers, aquaculturists	Water managers, aquaculturists	Aquaculturists
Location	Prince Edward Island, Canada	Sanggou Bay, China	Hardangerfjord, Norway	Ireland	Valdivia Estuary, Chile	Norway	Venezuela, China
Scale	Bay	Bay	Bay, local	Bay, local	Local (open water)	Local	Local (pond culture)
Cultured species	Blue mussel	Finfish, shellfish & seaweeds	Finfish & shellfish	Shellfish	Shellfish & finfish	Finfish	Penaeid shrimp
Data & information types	Field, experimental	Field, experimental, GIS, remote sensing	Field, GIS, desk-based	Field, experimental	Field, experimental, economic	Field	Field, experimental
Tools & model types	GIS, dynamic system-scale models	Dynamic system-scale models, catchment models, etc. (multilayered)	GIS, socio-economic instruments, models	Combined GIS & dynamic models	Dynamic models, statistical models	Sensors, risk assessment models	Dynamic models
Platform	Console	console/Web	Web	Console	Web/console	Web	Web/console
Decision-support	Licensing, production & environmental effects	Licensing, species combinations, production & environmental effects	Management monitoring, site selection & licensing	Licensing, production & environmental effects	Production, economic optimization, environmental effects	Production, disease & animal welfare	Production, economic analysis & environmental effects
Costs (medium: USD104–105; high: USD 105–106)	Medium	High	Medium	Medium	Medium	Medium	Medium
Time (estimated for a 5–10 person team)	Months–years	Years	Months–years	Months–years	Months	Months	Months
Technical skills (high: develop & apply models, medium: apply existing models)	High	High	High	High	Medium	Medium	Medium

products in supporting ICZM, assisting water managers in the licensing process (system scale), and helping aquaculture farmers in selecting sites and optimizing production. The case studies shown focus also on various aspects of environmental sustainability.

The selected case studies represent a broad sampling across geographic regions. They vary with regard to the degree to which outcomes have been used for practical decision-making and to the complexity of the analytical methods used. Each of the case studies is presented in the following format:

- source of the work;
- objectives;
- target audience;
- geographic area and scale of analysis;
- analytical framework and results; and
- relevance of virtual technology and decision support for management.

Case study 1: Prince Edward Island: system-scale carrying capacity (source: Filgueira and Grant, 2009)

Objectives

Canada's smallest province, Prince Edward Island (PEI), is home to the nation's largest blue mussel (*Mytilus edulis*) culture industry (80 percent of production), with an annual yield of 17 000 tonnes. Typical problems of extensive shellfish culture have been encountered, including overstocking and reduced growth, fouling by tunicates and eutrophication impacts. Although there are studies of mussel culture in various bays of PEI (e.g. Cranford, Hargrave and Doucette, 2009), the location with most research focus has been Tracadie Bay, on the north shore, which includes 20 percent of PEI's production. In terms of research, simulation models of circulation, biodeposition, seston depletion and mussel growth have been developed, coupled to comprehensive field programmes (e.g. Grant *et al*., 2008).

Ecosystem modelling provides a method of managing entire culture ecosystems, with the goal of developing sustainable levels of aquaculture through marine spatial planning. In this example from eastern Canada, the modelling approach is presented, as well as criteria for sustainability within the model context. Despite this capability, only some of the research has been closely matched to management schemes.

Target audience

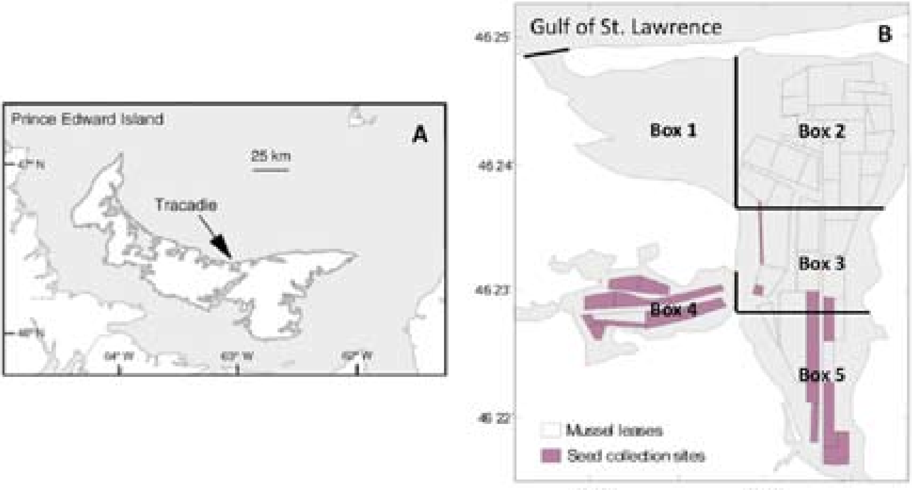
The regulatory authority, the Department of Fisheries and Oceans Canada (DFO), has an advisory capacity established with the mussel industry. The industry is integrated within the PEI Aquaculture Alliance. Naturally, mussel growers seek to maximize production in the bay, and form management committees with DFO. Strategies such as reduction in longline spacing (Comeau *et al*., 2008) have been utilized, but trial and error adjustments are risky to implement and do not integrate the interaction between culture in different parts of the bay. The virtual tool most targeted toward culture advice is that of Filgueira and Grant (2009), where a box model of seston depletion was constructed for Tracadie Bay. Under different stocking densities, resulting seston depletion was observed and compared to a quantitative sustainability criterion as detailed below.

Geographic area and scale of analysis

The 130 growers of PEI use the many shallow barrier island estuaries typical of the island's sedimentary coastline. Longline culture is practiced exclusively. American cupped oysters (*Crassostrea virginica*) are also grown, but there is primarily a bottom fishery for oysters. Due to the accessibility of culture areas, protected waters and a productive environment, mussel culture occupies significant portions of many bays. Tracadie Bay is among the most intensively studied coastal areas of eastern Canada. Culture maps demonstrate the extent to which mussel farms dominate the surface area of the bay (Figure 3).

Depths range to only 6 m and much of the bay is 3 m deep. Discrete bays with narrow inlets arguably constitute distinct ecosystems, separated from adjacent systems by open ocean. Research and management at this level may therefore be considered ecosystem scale.

FIGURE 3
Tracadie Bay showing model boxes and the location of mussel culture leases. The width of Box 2 is ~2 km



Source: Filgueira and Grant (2009).

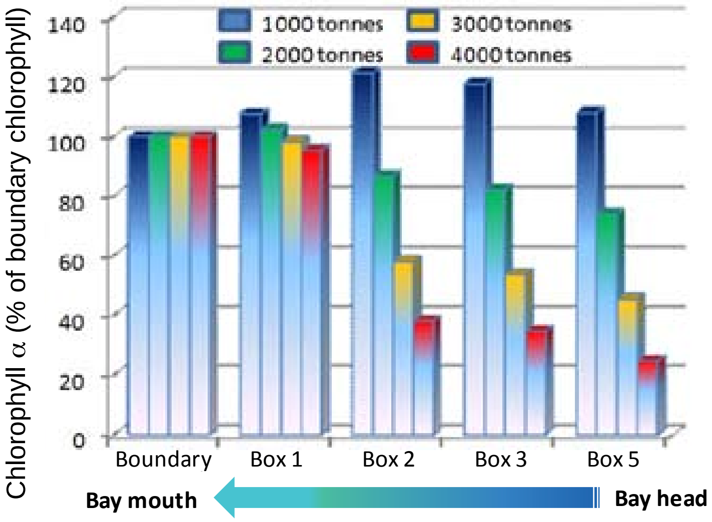
Analytical framework and results

Although carrying capacity may have a variety of contexts and definitions, Filgueira and Grant (2009) worked with ecological carrying capacity, meaning that the trophic functioning of the system would not be degraded by the level of culture deployed in the bay.

In practical terms, there was a focus on the limiting resource for bivalves, phytoplankton measured as chlorophyll. If bivalves deplete this resource far below natural levels, food for plankton, including larval fishes, as well as benthic organisms, would be reduced. These dynamics were simulated using a box model (Figure 3), and the output from a 2D circulation model of the bay.

Chlorophyll at the tidal inlet is a measure of primary production entering the system through boundary conditions; the ratio of internal chlorophyll to boundary chlorophyll is a measure of how mussel grazing (among other internal sinks) reduces this supply. The annual variation in this ratio is an indication of noise in the system, determined to be Coefficient of Variation = 27 percent in this study. These values are plotted for each box as a function of mussel stocking biomass (Figure 4). It is important to recognize that there is generally exchange limitation within the bay from outer (Box 1) to interior boxes (Box 5), including reduced mussel growth (Waite, Grant and Davidson, 2005). It can be seen that for a standing stock of 1 000 tonnes total fresh weight (TFW), there is no depletion, and even positive effects as primary production increases chlorophyll within the bay. For a doubling of this standing stock, there is some decline in relative chlorophyll toward the upper bay, but within the expected variation of changes in phytoplankton biomass compared to boundary values. The latter standing stock is thus sustainable according to a functional criterion.

FIGURE 4
Model results of relative chlorophyll depletion in Tracadie Bay as a function of mussel standing stock along the main axis of the bay from the tidal inlet (boundary) to the head of the bay (Box 5)



Source: Adapted from Filgueira and Grant (2009).

For even higher standing stock, chlorophyll is severely reduced compared to its natural range of variation, and the ecosystem is presumably compromised. Adjusting the standing stock in the various boxes is one solution to these limitations, but becomes an optimization problem, requiring a further stage in the modelling. Therefore, using a spatially coarse box model with objective standards for carrying capacity defined by the seston dynamics, aquaculture can be managed on the basis of ecosystem-level considerations.

Relevance of virtual technology and decision support for management

Mathematical models comprise one of the most powerful virtual tools due to their predictive capability arising from retrospective analysis – the ability to run "what-if" scenarios. Box models are obviously less spatially resolved than fully spatial models, and as a result less inclined toward mapped results. However, the transects of seston depletion we have shown, including a limit for acceptable change, allow a visual view of seston levels under various stocking scenarios.

Optimization routines can be used to select biomass levels that do not steepen the depletion gradient excessively. There are shellfish growth rates associated with these farming densities, which can also be used in predicting the consequences of food density for bay yield. Decision support is most likely undertaken with researchers, but the objectives of either managers or shellfish farmers are the prime consideration in applying the model. Careful consultations with these stakeholders is required, as well as the ability to validate the model with field measurements, such as bivalve growth.

Case study 2: SPEAR – Sustainable Options for People, Catchment and Aquatic Resources

(source: Ferreira *et al.*, 2008a)

Objectives

The general objective of SPEAR (Ferreira *et al.*, 2008a; http://biaoqiang.org) was to develop and test an integrated framework for management of the coastal zone, using two test cases where communities depend primarily upon marine resources, of which a large component is aquaculture of finfish, shellfish and seaweeds, often in IMTA.

Target audience

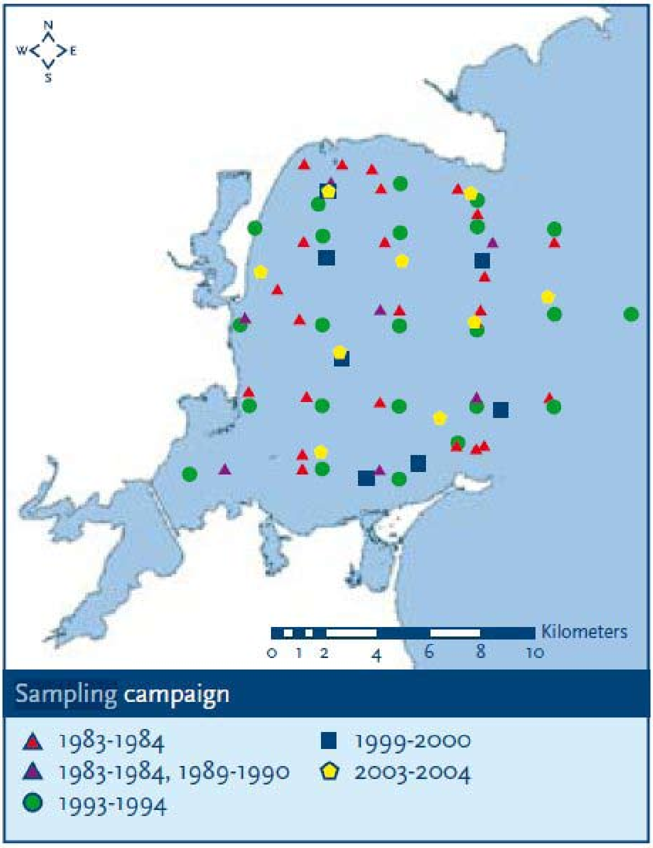
This type of system-scale model of carrying capacity is aimed specifically at water managers, planners and licensing authorities. It provides information on the system as a whole, with an appropriate degree of spatial discrimination, in order to set overall limits for sustainable aquaculture, which may then be used to inform more detailed (local-scale) siting and licensing.

Geographic area and scale of analysis

Two contrasting coastal systems in China were used as study areas. Sanggou Bay (Shandong Province) is in a northern rural area and Huangdun Bay (Zhejiang Province) in a heavily industrialized area with substantial human pressure on both local and regional levels. The case study reported herein refers specifically to Sanggou Bay (37oN, 122oE), located within the jurisdiction of the small (population 150 000) city of Rongcheng. Weihai is the closest larger city, with a population of 2.5 million. Sanggou Bay (Figure 5) is a semicircular embayment with an open boundary to the sea. The water exchange is chiefly forced by the tides, and the bay is well mixed, both horizontally and vertically, with a residence time of 5–20 days.

FIGURE 5

Sanggou Bay, northeast China, showing sampling stations



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

The aquaculture production in Sanggou Bay is 263 500 tonnes/year and consists of cultivated species of seaweeds, shellfish and finfish, of paramount importance for community income and livelihood, both locally and regionally.

Analytical framework and results

The well-tested EcoWin2000 (E2K) ecological model (Ferreira, 1995; Nunes *et al*., 2003; Nobre *et al*., 2010) was used to simulate aquaculture production of multiple shellfish species simultaneously. Organic inputs from finfish aquaculture and seaweed production were also modelled. Circulation was modelled by coupling outputs of the detailed hydrodynamic simulations offline (using the Delft3D model), upscaled to a 3D ecological model with two vertical layers (16 boxes). The water flows derived for a grid with 60 000 cells and with a timestep of three minutes were upscaled to larger boxes and a timestep of one hour, and used to force the transport of substances in the larger box model.

The biogeochemical state variables are simulated for each box using as forcing functions (i) boundary loads: catchment (simulated using the SWAT model), ocean boundary, using measured data, and aquaculture emissions; and (ii) light climate and water temperature. The approach thus brings together a set of models that run at different time and spatial scales, and for different ecosystem components. A key feature of the general modelling approach is to integrate the several models in order to develop a robust ecosystem modelling framework; this requires the assembly of a wide range of data. The general framework for application is described in Ferreira *et al*. (2008a) and Nobre *et al*. (2010).

The E2K outputs for harvested shellfish and macroalgae are shown in Table 6. It should be noted that the only validation possible for these results is by comparison to landings data, which are somewhat unreliable. For that reason we discourage a modelling approach where models are calibrated to match reported harvests, and in this application of E2K, the calibration and validation were performed for several water quality variables, including drivers of shellfish growth, and for the underlying models for catchment loading, water circulation and individual growth.

Despite this caveat, for Sanggou Bay the modelling system led to the harvest results shown, which compare well with the survey data.

TABLE 6
Landings data and modelled harvests for Sanggou Bay (tonnes/year)

Pacific cupped oyster *(Crassostrea gigas)*		**Farrer's scallop** *(Chlamys farreri)*		**Kelp** *(Laminaria japonica)*		**Total**	
Landings	**Model**	**Landings**	**Model**	**Landings**	**Model**	**Landings**	**Model**
178 872	175 382	5 000	5 148	84 500	83 754	268 372	264 284
	(-2%)		(+3%)		(-1%)		(-1.5%)

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

Relevance of virtual technology and decision support for management

The full ecological model for Sanggou Bay has over 100 state variables, and is able to simulate a period of three years in under five minutes. This makes it possible for decision-makers to quickly examine development scenarios. An example of the use of the model for decision support is summarized below.

Reduction of shellfish culture densities

Shellfish aquaculture is the largest industry in Sanggou Bay, and the major source of revenue to Rongcheng City. Due to the strong desire for increased economic benefit, farmers have substantially increased shellfish seeding density since the late 1990s. However, yields have been limited by a combination of reduced growth (potentially due to overstocking) and infectious diseases, particularly in the Farrer's scallop.

This scenario considers a reduction of 50 percent in seeding density, in order to analyze changes in both harvest tonnage and revenue. Table 7 shows the results of the application of E2K to Sanggou Bay for both the standard and scenario simulations. The results suggest that a 50 percent reduction in stocking density would lead to a 31 percent decrease of Pacific cupped oyster harvest and a 220 percent increase in Farrer's scallop harvest. The simulation results indicate an overall decrease in harvest of 24 percent for a 50 percent reduction in density, suggesting that the carrying capacity of Sanggou Bay is largely exceeded. Additionally, because of the price differential between Farrer's scallop (a high value crop) and Pacific cupped oyster, the total income from shellfish aquaculture is identical.

TABLE 7

Application of E2K to Sanggou Bay, to analyze changes in yield and profitability associated to a 50 percent reduction in shellfish culture

Shellfish species	Pacific cupped oyster		Farrer's scallop	
	Standard model	Reduction scenario	Standard model	Reduction scenario
Seeding density (ind/m^2)	70	35	60	30
Percentage change	–	-50%	–	-50%
Harvest (tonnes)	175 382	121 413	5 148	16 472
Percentage change	–	-31%	–	+220%
Revenue (CYN10^6)	102	72	15	46
Percentage change	–	-29%	–	+207%

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

There is a significant growth depression in Farrer's scallop in the standard simulation, when compared with the scenario, which suggests that (i) the seeding density is too high; and (ii) the food depletion caused by the surrounding large-scale Pacific cupped oyster culture significantly limited the growth of Farrer's scallop, while their cultivation area ratio is 2.6:1. There is a remarkable growth increase in both species when the seeding density is halved.

Case study 3: AkvaVis decision support system

(Source: Ervik *et al.*, 2008)

Objective

The decision support system AkvaVis (Figure 6) for site selection, carrying capacity and management monitoring is presently under development (Ervik *et al*., 2008). AkvaVis aims to develop a Web-based interface that will be transparent to public insight and dynamic in the sense that it is adaptable to new knowledge, new regulatory frameworks, and demands from industry and public and private stakeholders.

The challenges of integrated planning and management for aquaculture in the Norwegian coastal zone have prompted the launching of a new cohesive management system MOLO (environmental monitoring – location), under which AkvaVis is intended to be developed as the virtual decision-support tool.

Target audience

The target audience includes all stakeholders in the fields of aquaculture production, management and policy implementation. A user survey (Hageberg, 2008) is part of the current development of the system.

Geographic area and scale of analysis

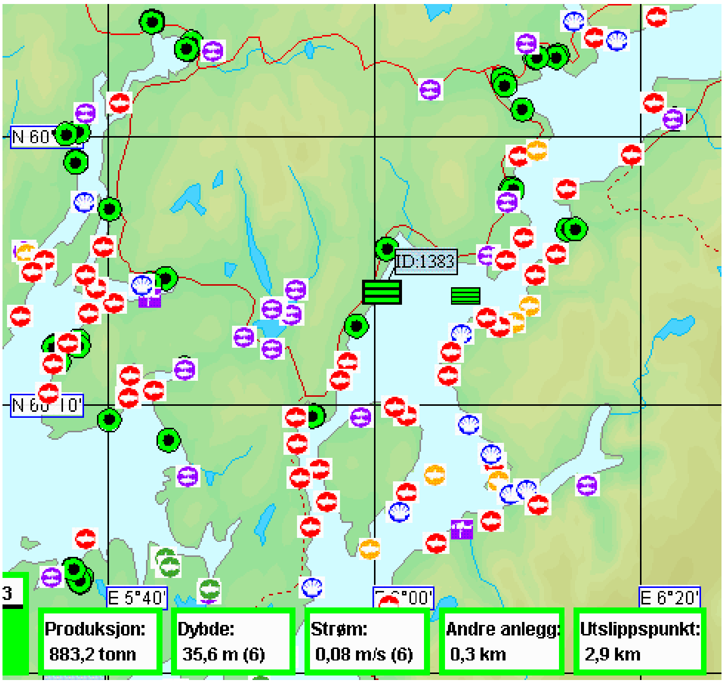
AkvaVis aims at covering the main aquaculture species in Norway, and demonstrations for the blue mussel and Atlantic salmon (*Salmo salar*) in the Hardangerfjord are available at www.akvavis.no.

Analytical framework and results

AkvaVis is built up of three modules that share the same databases and information but apply it for different purposes. The siting module can identify potential farm sites and simulate their carrying capacity, the management module will compile all available information needed by the authorities for aquaculture management, and the application module will aid in an efficient application procedure and ensure that all relevant information is provided. AkvaVis divides the relevant area into grid cells and objects containing quantitative information on localization parameters. The user can insert into the map an “intelligent farm object” that communicates dynamically with a mathematical model using the information in the grid as input for simulating aspects of production and ecological carrying capacity as well as with information on other objects.

Once inserted, the “intelligent object” will thus immediately report back how suitable a given site would be for mussel or fish farming by giving a score for each parameter and a calculated total score on how the requirements are met.

FIGURE 6
The AkvaVis site selection expert system



Produksjon: 883,2 tonn
Dybde: 35,6 m (6)
Strøm: 0,08 m/s (6)
Andre anlegg: 0,3 km
Utslippspunkt: 2,9 km

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

Siting of a salmon farm will interact with a conformed version of the MOM model (Ervik *et al.*, 1997), assessing the potential effects on the bottom and on benthic fauna returning suitability according to environmental impact standards. AkvaVis is developed using a map client based on the web map service (WMS) standard. The system integrates: (i) data regarding parameters (e.g. currents, aquaculture sites and waste outlets); (ii) expertise (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. The interactivity allows the users to immediately see the consequences of their choices.

Relevance of virtual technology and decision support for management

The AkvaVis DSS will provide a hands-on Web-based interface that will give the user immediate response to choices. The siting, management and application modules are purpose-designed to meet some of the prime needs in aquaculture management by authorities and industry.

The transparency to public insight and dynamism to new knowledge, new regulatory frameworks and demands from industry and public and private stakeholders is regarded as important for development of an efficient and trustable tool.

Case study 4: UISCE Project Virtual Aquaculture (GIS modelling application for bay and site-specific aquaculture production scenarios) (Source: Dallaghan, 2009)

Objectives

The objectives of the Understanding Irish Shellfish Culture Environments (UISCE) project were to: (i) develop a suite of computer models to facilitate the prediction of different aquaculture and water quality scenarios which could influence the nature and/or scale of shellfish aquaculture activity in a bay area; (ii) provide a decision support system, based on the suite of computer models, to the aquaculture industry with respect to the best locations and optimal size of shellfish aquaculture sites; and (iii) to provide an information base and liaison facility for industry.

Target audience

The target audience includes all stakeholders in the fields of aquaculture production, management and policy implementation.

Geographic area and scale of analysis

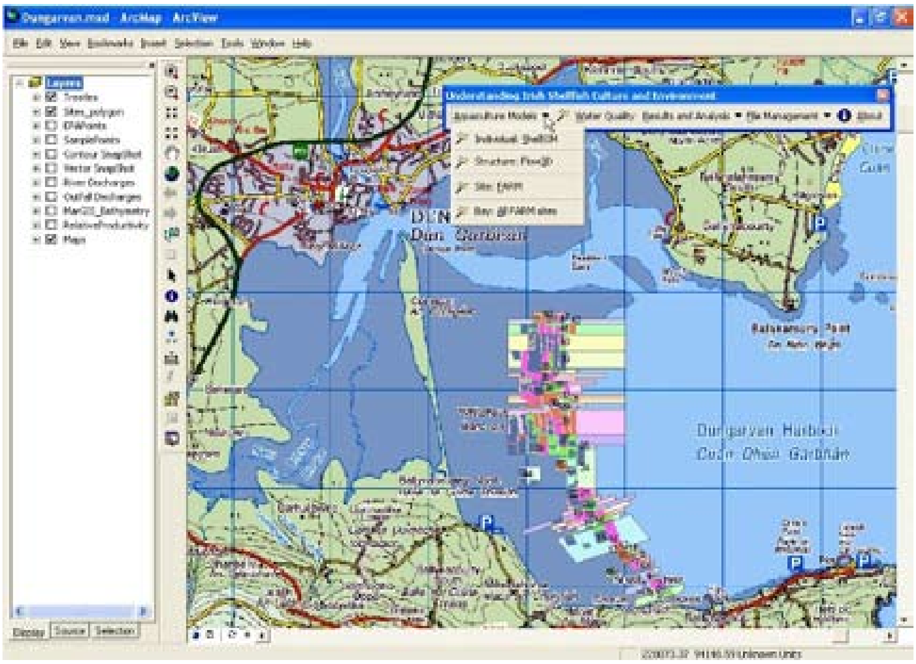
MarGIS™ has been adopted by the Northwest Region of the United Kingdom Environment Agency, and is currently used on the Mersey, Ribble and Severn estuaries and in Morecambe Bay in the United Kingdom.

Analytical framework and results

The MarGIS™ DSS, constructed as part of the UISCE project, is a near real-time interactive software application, tailored specifically for shellfish growers around the Irish coast, which will enable them to optimize their operations and production in a sustainable and environmentally sensitive manner. By using near real-time current conditions, MarGIS™ will allow a farmer to quickly see what effect on his productivity would be expected if he were to make stocking density changes, for example, or to reposition one or all of his mussel lines, or introduce more mussel lines in the vicinity of the existing farm. By allowing the optimization of husbandry techniques such as this, the software encourages farmers and communities to work together.

MarGIS™ has been developed within the ESRI ArcView environment to facilitate location-specific predictions from the suite of computer models and allows for the modelling and reporting on issues surrounding the shellfish aquaculture industry from a “macro” or bay-scale level through to a “micro” or individual animal level (Figure 7).

FIGURE 7
Menu options of the MarGIS™ UISCE application



Source: Dallaghan (2009).

The primary deliverable from the UISCE project is a desktop application that can be used repeatedly by growers with functionality added and refined as required. This system gives growers access to the best science available and the knowledge, in software form, of international experts. The system makes it easier to understand embayment from a food and flow perspective, thus allowing growers to move away from "trial and error" aquaculture. The data generated by this project form an information base for industry and other state agencies. This data can be built upon and put to a variety of uses. An online demonstration of MarGIS™ is available at www.marcon.ie/website/html/margisdemo.htm.

Relevance of virtual technology and decision support for management

MarGIS™ is especially relevant for novel management of aquaculture for a number of reasons: it can be used to infer near real-time scenarios of environmental impacts of aquaculture at both farm and bay scales; the application encourages farmers and communities to work together, thus ensuring stakeholder inputs and participation; it centralizes the best science available in the fields of shellfish growth, aquaculture, water quality and ecological models and it places all this expertise under one roof. The integration of models with the GIS framework and the construction of a mechanism whereby models could communicate to each other was one of the project cornerstones.

MarGIS™ will allow farmers to quickly and accurately identify the carrying capacity of their bay and what impact changes to the density of their farming stock would have on production levels. This was one of the main drivers of the project, with anecdotal evidence of suboptimal growth for mussels in Killary Harbour suggesting that possible over-stocking of some sites in the bay may have been leading to poor growth rates.

Case study 5: Farm Aquaculture Resource Management (FARM) (Source: Silva, 2009)

Objectives and target audience

FARM (Ferreira, Hawkins and Bricker, 2007) was initially developed to provide a simple tool for application by shellfish farmers and a means for rapid screening of cultivation potential in data-poor environments, which typically occur in developing nations. Complementary approaches may be used for carrying capacity analysis, such as remote sensing techniques for chlorophyll, turbidity and other variables (Grant *et al*., 2009). However, these may be hampered (i) for smaller systems by the available spatial resolution of images; and (ii) for Case II (inshore, brackish) waters, by algorithm accuracy, although this is improving rapidly (e.g. Moses *et al*., 2009).

More recently, the approach has been extended to finfish cage culture, and as such can also address IMTA. Whether FARM is applied in systems where lots of data are available or in those where better data are needed, the model is a decision-support tool for (i) site selection; and (ii) expansion/optimization of existing farms, and as such of interest to managers, aquaculturists and regulatory agencies.

Geographic area and scale of analysis

The FARM model simulates the individual growth of shellfish and finfish in open water, taking into account food supply and oceanographic conditions, and calculates the distribution of biomass for cultivated species, with an emphasis on the harvestable weight classes. It is designed to be used for local-scale (hundreds to thousands of meters) assessment of carrying capacity.

The FARM model has been tested in the European Union (France, Ireland, Italy, Portugal, Scotland, Slovenia; Ferreira *et al*., 2009), the United States of America (Puget Sound and Chesapeake Bay), China (Ferreira *et al*., 2008a) and Chile (Silva, 2009). The Web version has been viewed from 67 countries, from all continents, so it is likely that the model has been applied far more widely.

Analytical framework and results

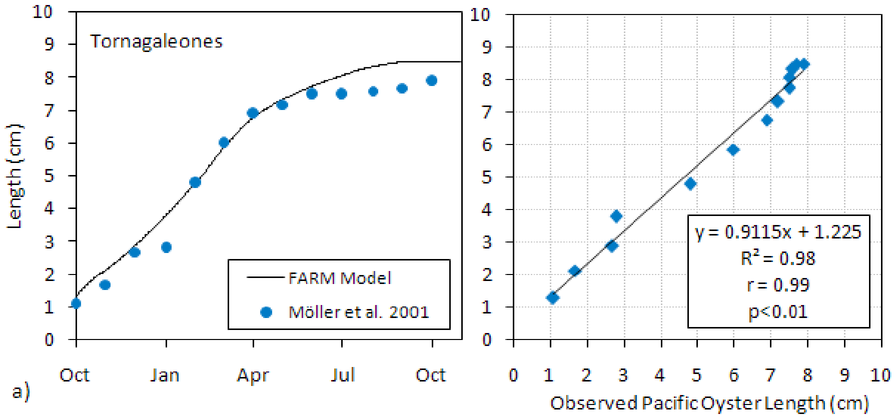
As an example application, FARM was used to test three sites in the small (15 km^2) Chilean estuary of Valdivia, to screen for potential oyster farming areas (Silva, 2009).

The individual growth model used for *Crassostrea gigas* (AquaShell^{TM}) is based on a net energy balance approach (e.g. Hoffmann *et al*, 1995; Kobayashi *et al*., 1997) and draws on functions for feeding, assimilation and metabolism published by various authors (Dame, 1972; Hoffmann *et al*, 1995; Kobayashi *et al*., 1997; Ren and Ross, 2001, Brigolin *et al*., 2009). It simulates: (i) change in individual weight (growth), expressed as tissue dry weight and scaled to total fresh weight (with shell) and to shell length; and (ii) functional dependency on relevant physical and biogeochemical components (i.e. allometry, total particulate matter, temperature and salinity) and partitions the phytoplankton and detrital food resources; and (iii) provides environmental feedbacks for production of particulate organic waste (faeces and pseudofaeces), excretion of dissolved nitrogen and oxygen consumption.

The individual model was validated using experimental growth curves determined by Möller *et al*. (2001) for the Valdivia Estuary and showed a significant relationship ($p<0.01$) to measured growth (Figure 8).

Data were available at the site area for a one year period for the environmental drivers used in FARM, and the model was used to screen potential growth as shown in Table 8. The model outputs for a standard simulation of *C. gigas* in suspended culture (Table 8, column 2) suggest this is a promising area for oyster cultivation, with fast growth and a good return on investment, as shown by the average physical product (APP = output : input) ratio of 11.6, and by the predicted income. The sediment accretion rate and organic enrichment due to shellfish biodeposits (41 percent increase in POC/year over background sedimentation of organic carbon) are both low.

FIGURE 8
Validation of individual growth for the Pacific cupped oyster (*Crassostrea gigas*) in Valdivia Estuary, Chile



Source: Silva (2009).

Two sites at other locations in the estuary were screened, and on the basis of APP found to be borderline suitable (APP = 1.57), and unsuitable (APP = 0.22), even at low cultivation densities, and thus rejected.

A marginal analysis (Ferreira, Hawkins and Bricker, 2007) was performed for profit optimization of the Tornagaleones site by plotting the marginal physical product (MPP, the first derivative of TPP) at increased seeding densities and graphically determining the optimum based on financial data (Table 8, column 3).

TABLE 8

Inputs and outputs of FARM for initial screening, optimization analysis and IMTA at a potential *Crassostrea gigas* farm in the south Chilean estuary of Valdivia

Variable	Tornagaleones (TG) site	TG site optimized	TG site IMTA
Model inputs			
Farm area (m^2)	60 000	60 000	60 000
Seeding density (tonnes TFW)*	12	210	12
Culture period (days)	395	395	395
Seed weight (g)	1.2	1.2	1.2
Harvest weight (g)	90	90	90
Natural mortality (per year)	0.35	0.35	0.35
Model outputs			
Production			
Total physical product (TPP) (tonnes TFW)	139.6	952.5	154.0
Average physical product (APP)	11.6	4.54	12.8
Environmental impact			
Deposition of POC (kg/m^2/year)	7.64	10.44	9.96
Sediment organic enrichment (% POC/year)	6.88	9.03	8.66
Sediment accretion rate (mm/year)	7.73	10.57	10.08
Carbon removal (kg C/year)			
Phytoplankton removal	8 860	117 015	8 966
Detritus removal	60 000	866 008	62 086
Nitrogen removal (kg N/year)			
Phytoplankton	-1 378	-18 202	-1 395
Detritus	-9 333	-134 712	-9 658
Excretion	576	8 129	587
Faeces	4 942	70 997	5 108
Mortality	81	1138	83
Mass balance	-5 111	-72 651	-5 274
Population equivalents (PEQ/year)	1 549	22 015	1 598
Income**			
Shellfish farming (1000 €/year)	645.2	4 400.6	711.4
Nitrogen removal (1000 €/year)	46.5	660.5	47.9
Total (k €/year)	691.7	5 061.0	759.4***

Terminology: particulate organic carbon (POC).

* TFW = total fresh weight (with shell).

** Price of input (cost of seed): 1 €/kg, price of output (sale): 5 €/ kg.

*** Does not include revenue from finfish culture.

Source: Silva (2009).

Optimum profit is achieved with a substantially higher stocking density (210 tonnes TFW), at a decreased, but still very attractive, APP of 4.5. Negative effects on the sediment show an increase of the order of 50 percent, and there is a marked reduction (about 25 percent) in water column chlorophyll and organic detritus. Farmers often strive to achieve maximum production (i.e. by maximizing income), which can be well beyond the optimum profit point, providing a diminishing return on investment and greater environmental damage.

The TPP of 139.6 tonnes shown in the standard model (Table 8, column 2) is distributed over three 2 ha sections, which show progressively lower yields due to food depletion (40 percent, 33 percent and 27 percent, respectively from upstream to downstream). Fish cages were added in the two downstream sections of the farm (five cages with 1 000 fish in each section) to simulate an IMTA scenario (Table 8, column 4).

The particulate organic material from fish culture improves the overall yield by 10 percent and increases the APP to 12.8. The combined finfish production and increase in shellfish yield provides a supplementary source of revenue to the farmer, at a small cost in terms of increased biodeposition. The shellfish additionally provide an important environmental service by filtering a part of the uneaten food and solid waste from the finfish culture, which would otherwise potentially lead to organic enrichment of underlying sediment.

Relevance of virtual technology and decision support for management

The modelling system combines hydrodynamics, physiology and population dynamics, water quality and eutrophication models that together produce the outputs shown in Table 9.

All of these outputs are valuable in informing, siting, licensing and operating shellfish and finfish farms, both from the production angle and with respect to environmental effects.

TABLE 9
Outputs and applications of FARM

Output	Applications
Harvestable biomass over the cultivation period	Simulation of potential harvest; optimization of harvest timing; changes of seed density, mortality, food supply, etc.
Marginal analysis of production	Determination of optimum profit structure with respect to seeding. Determination of APP and marginal physical product (MPP)
Release of dissolved and particulate matter	Determination of biodeposition, potential consequences for sediment oxygen demand
ASSETS eutrophication model based on inflow & outflow water quality	Effect of the farm on water quality – shellfish farms tend to improve water quality, finfish farms have the opposite effect. Simulation of combinations in IMTA
Mass balance for carbon & nitrogen	Establish the carbon footprint of a farm, determine the role of shellfish farms in reduction of eutrophication symptoms, & the farm value for nutrient credit trading in ICZM

Source: Silva (2009).

Dynamic models provide a number of advantages over more traditional approaches, e.g. by explicitly simulating extreme events such as mortality due to oxygen stress in intertidal areas or contextualizing biodeposition from a farm in the light of natural patterns for the area. Rich data sets will improve confidence in model outputs, but even in data-poor contexts, this kind of screening model can support the licensing process, assist with farm financing and help managers decide on acceptable environmental trade-offs.

Case study 6: Welfaremeter

(Source: Stien *et al.*, 2008a,b; Stien, Kristiansen and Torgersen, 2010)

Objectives

Although a sea cage can contain fish worth over a million euros, the monitoring of the cage environment and fish behaviour is typically kept at a minimum. The reasons for the low monitoring level are both lack of suitable monitoring equipment and lack of computer systems for handling and interpreting large amounts of data. The Animal Welfare Group at the Institute of Marine Research (IMR – Norway) addressed this deficiency by developing a system for monitoring of cage environment, fish behaviour and automatic assessment of fish welfare in aquaculture sea cages.

The system is called Welfaremeter (Figure 9) and began as part of the EU project 022720 FASTFISH and the RCN project 179878 Velferdsmåler and is now continued in the RCN project 190259 WELFARE-TOOLS (W-T). W-T is also funded by The Fishery and Aquaculture Industry Research Fund (FHF) and Nord-Trøndelag Fylkeskommune.

The prototype version of the system has been tested for two years in a commercial salmon farm, with promising results, and is now moving from prototype to a finished product. This second generation of the Welfaremeter is scheduled to be tested at two commercial farms from June 2010.

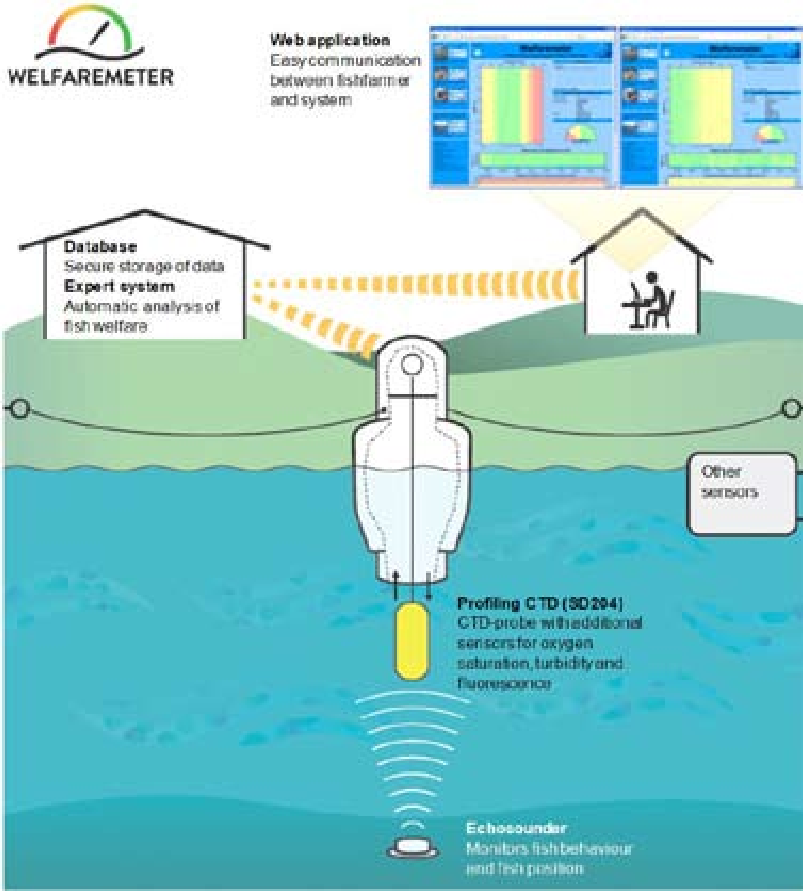
Target audience

The target audience includes all stakeholders in the fields of aquaculture production, management, research and policy implementation. Data from the system can also be part of surveillance of coastal waters.

Geographic area and scale of analysis

The first versions of the Welfaremeter are developed for salmon aquaculture in Norway. After the initial test period, there are plans to make the Welfaremeter available to other countries and to be extended to also cover other species (e.g. cod and seabass). If the system is adopted by the aquaculture community, it will provide data from a range of different sites on a continuous basis.

FIGURE 9
Schematic illustration of the Welfaremeter system



Source: Stien *et al*. (2008a,b); Stien, Kristiansen and Torgersen (2010).

Analytical framework and results

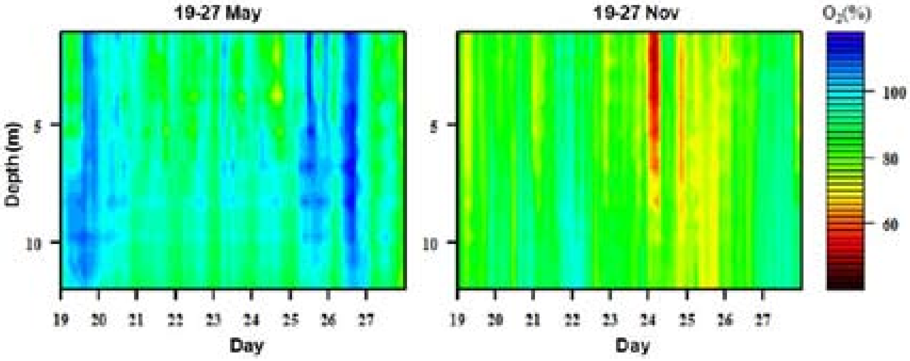
The Welfaremeter is a collection of products that together document and analyze the conditions in a sea cage. These products include different measuring systems such as profiling conductivity, temperature and depth (CTD) instruments and echosounders, a database for safe storage of the data, an expert software program for analysis of the data, and an Internet application for easy viewing of the data and the results from the expert software.

Profiling CTD

Several studies show that conditions in a sea cage can vary with season, during the day and throughout the water column (e.g. Johansson *et al*., 2007; Oppedal, Dempster and Stien, 2011).

FIGURE 10

Variation in oxygen saturation over time and throughout the depth of a salmon sea cage measured by the Welfaremeter system profiling CTD



Source: Stien *et al*. (2008b); Stien, Kristiansen and Torgersen (2010).

These studies also show that measuring water quality outside a sea cage provides limited information of the environment experienced by the fish; e.g. Vigen (2008) observed highly variable and minimum 30 percent oxygen saturation inside a sea cage, even though the oxygen saturation outside the sea cage was near 100 percent. In consequence, it is necessary to measure the environmental conditions frequently inside a sea cage, and for the entire water column. A central component of the Welfaremeter is therefore a buoy (APB505, SAIV AS, Norway) with a profiling CTD. The buoy winches the CTD up and down in the sea cage at predefined intervals, measuring temperature, salinity, oxygen, fluorescence, and turbidity for the entire water column of the sea cage (Figure 10).

Echosounder

In cages with a clear stratification in water quality, farmed salmon position themselves in order to be close to their optimum environment (Johansson *et al*., 2006; Oppedal, Dempster and Stien, 2011). Atlantic salmon have, for instance, been observed to prefer temperatures between 16 and 18 °C within a range of 11 to 20 °C (Johansson *et al*., 2006). By including echosounder data, it is possible to know the water quality actually experienced by the fish, thus providing more accurate input to the expert software's models for fish growth and fish welfare (see below). Furthermore, if the fish position themselves at suboptimal water quality, this may be an indicator of disease or an immune-compromised state. The expert system compares the experienced and expected swimming depths as a behavioural indicator of the well-being of the fish. As an example, lack of activity towards surface feeding events may indicate poor welfare (Juell *et al*., 1994).

Database, expert software and Internet application

The data from the different measuring systems are automatically stored in a central database. When new data arrive in the database, they are analyzed by the expert software. In addition to looking for abnormal vertical position (see above), the software uses data on the water quality to calculate a welfare index from 0 (terrible welfare) to 100 (excellent welfare). This index is based on modelling of metabolic scope (the capacity of fish to extract oxygen from the water beyond their basic needs) and is a measure of how much stress the fish can tolerate.

Relevance of virtual technology and decision support for management

The fish farmer can use the welfare index when managing meal times, feed amounts and to decide if operations (e.g. cleaning of the nets) can be performed or should be postponed. Both the incoming data and the results from the expert system are shown in the Internet application (www.imr.no/welfaremeter).

During the summer of 2010, the Welfaremeter system was tested at two different commercial sites along the coast of Norway. The goal was both to test the robustness of the different parts of the Welfaremeter system and to evaluate and improve the expert software. The expert software should be able to give the fish farmer daily information to improve fish welfare and hence the productivity of the fish farm. Additional data sources will be added as manual input via the Internet application, e.g. data from a probe that measures water quality outside the cage, and SmartTag. SmartTag is a system developed by Nofima Marin and Thelma AS (Norway) that registers breathing patterns of individual fish.

Onsite data acquisition systems like the Welfaremeter have a great potential in integrated decision-support tools in order to increase dynamic response and efficiency. The Welfaremeter is intended to be integrated into the AkvaVis tool (see Case study 3).

Case study 7: Shrimp pond culture (POND)[3]

Objectives and target audience

The Pond Aquaculture Management and Development (POND) model simulates individual growth (Franco, Ferreira and Nobre, 2006) and population dynamics of cultivated penaeid shrimp. Additionally, it fully integrates the relevant components of water and sediment quality (e.g. Di Toro, 2001; Burford and Lorenzen, 2004; Simas and Ferreira, 2007; Vinatea *et al*., 2010), food decomposition, oxygen

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[3] Presentations by C. Zhu, J.G. Ferreira, M. Donato, A. Hawkins, X. Yan & A.Nobre on *LMPrawn – a model for management of cultivated penaeid shrimp* presented at ERF2007, Providence, Rhode Island, USA, 4–8 November 2007 and by C. Zhu on *Application of a shrimp farm management model to three types of shrimp farms in South China* presented at the Trilateral Symposium on Aquaculture Science among China, Japan and Korea, held in Guangzhou, China. October 22, 2009.

balance (e.g. Boyd, 1998; McGraw *et al*., 2001; Zhang *et al*., 2006) and effluent discharge. The economic aspects of the shrimp culture cycle (e.g. Kam, *et al.,* 2008) are also considered. The model is designed for shrimp pond aquaculture management, and has five main uses: (i) prediction of production and feed requirement; (ii) optimization of seeding size and culture period; (iii) optimization of farming methods (e.g. monoculture or IMTA with bivalves such as razor clam); (iv) analysis of impacts on water quality, important for certification and sustainable development (Boyd, 2009); and (v) profitability assessment, including evaluation of externalities. POND is currently applicable to the whiteleg shrimp (*Litopenaeus vannamei*) and Indian white prawn (*Fenneropenaeus indicus*), and IMTA of shrimp with other species (e.g. tilapia, bivalves) may also be simulated.

Geographic area and scale of analysis

POND has been successfully applied to shrimp farms in Venezuela and southern China. The model is designed for use by farmers and managers, at the scale of individual production ponds.

Analytical framework and results

POND computes individual growth of penaeid shrimp from the juvenile stage to the end of the culture cycle.

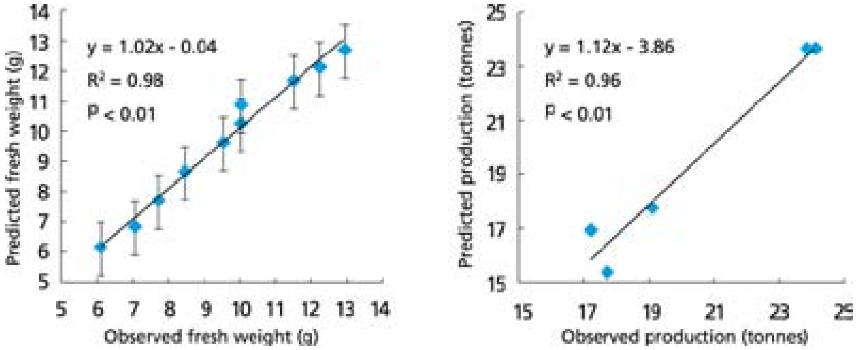
Shrimp larval stages (nauplius, zoea and mysis) have a very short duration of less than three weeks, and were not included. The growth model simulates five physiological processes: ingestion, assimilation, elimination of faeces, respiration and reproduction, and is forced by food availability, water temperature and dissolved oxygen. These are used to determine scope for growth at the population level, by considering the transition of individuals across an appropriate range of weight classes. Growth and mortality are combined in the population model, and allow the biomass of harvestable classes to be determined.

Validation results for *L. vannamei* individual growth and pond production for a farm in Venezuela are shown in Figure 11. The model is able to satisfactorily reproduce both the individual weight of the animals and the farm production, which suggests that it may be used for management purposes.

Relevance of virtual technology and decision support for management

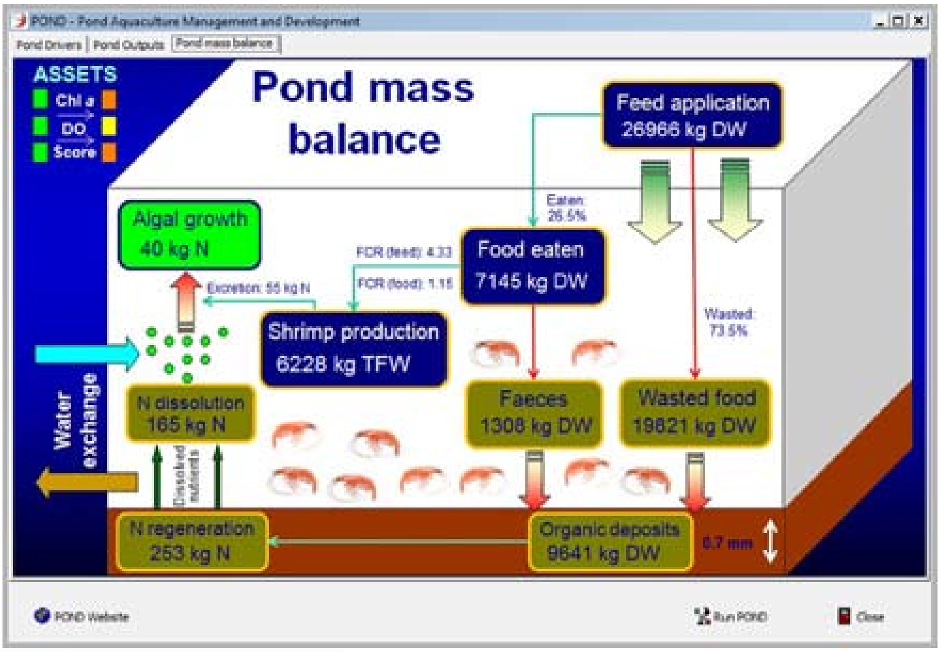
This case study is the only example which focuses on land-based pond culture, a very important component of aquaculture in Asia and Africa. The model explicitly simulates environmental effects, which allows the industry in developing nations to address certification issues and to determine the environmental footprint of shrimp farms, both with respect to discharge and sustainability of the ponds themselves.

FIGURE 11
Application of POND to shrimp pond culture in Venezuela (left pane: individual weight; right pane: pond production)



A simple version of the model may be run online at www.pondscale.com for assessment of production only, and a more detailed console version allows users to examine various aspects of the culture cycle, including waste feed, pond eutrophication and oxygen balance. Figure 12 shows the mass balance output for a simulation of whiteleg shrimp cultivated for a period of 110 days;

FIGURE 12
POND mass balance output for a 1 ha farm, including feed conversion ratio (FCR), diagenesis, primary production, effluent discharge and ASSETS eutrophication rating



Terminology: Nitrogen (N); Dry weight (DW); Total Fresh Weight (TFW).

Source: J.G. Ferreira and C.B. Zhu (unpublished).

food is administered on demand, and simulates the use of trays to inspect and adjust feed consumption by the animals, leading to a feed conversion ratio (FCR) of 1.7 and a minimal feed waste of around 11 percent.

Nitrogen supplied by excretory products from the shrimp and by sediment diagenesis drives algal growth, which in this example leads to a net primary production (NPP) of 46 kg of nitrogen over the culture cycle. POND constrains yield based on dissolved oxygen, which in the model conditions both individual growth (McGraw *et al.*, 2001) and population mortality (Zhang *et al.*, 2006).

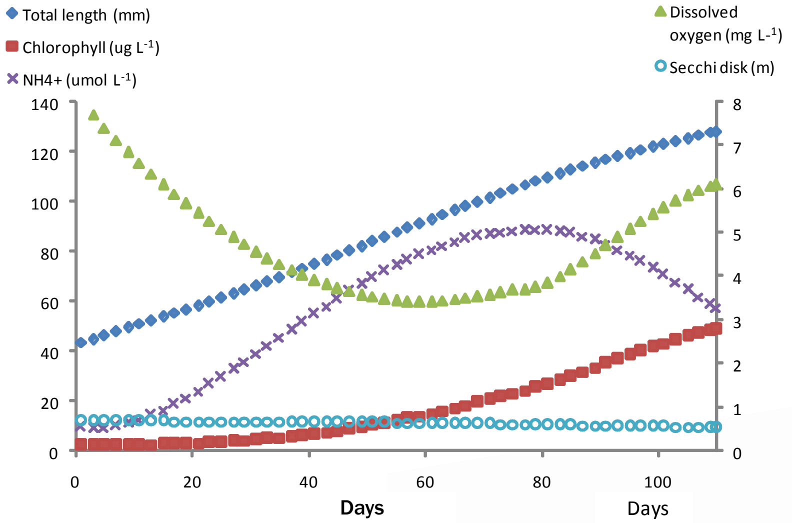
The mass balance in Figure 12 accounts for water renovation at a daily renewal rate of 3 percent of pond volume and determines the outflow of ammonia, particulate nitrogen (in phytoplankton) and chlorophyll over the culture period. The waste products discharged from farms correspond to a production cost which is not internalized, needs to be evaluated as part of an ecosystem approach to aquaculture, and will increasingly be required for product certification in western markets. Currently, pond production in the United States of America already requires a National Pollutant Discharge Elimination System (NPDES) permit (Boyd, 2009).

Over 60 kg of nitrogen (mostly dissolved, but also as algae) are discharged to the environment, roughly 20 population-equivalents per year for the 110 day cultivation cycle. The cost of abating that nitrogen discharge would be about USD800 (Lindahl *et al.*, 2005).

Figure 13 shows the model outputs for five environmental variables over the culture cycle. At harvest time, the total length of an individual is about 13 cm, for

FIGURE 13

Simulation results from a shrimp growth cycle. Total length of cultivated individuals, algal biomass, and ammonia (left axis), Secchi depth and dissolved oxygen (right axis)



an individual weight of 12.9 g. Chlorophyll increases more rapidly in the second half of the cycle, as more dissolved nitrogen becomes available in the pond, and the higher concentration of particulates reduces the Secchi depth from 67 cm at the start of the culture to a final value of 53 cm.

The percentile 10 (P_{10}) for dissolved oxygen in this example is 6.2 mg/liter in the inflow and 3.5 mg/liter in the pond and outflow. If the primary production component is switched off, the P_{10} in the pond falls to 2.7 mg/liter (40 percent saturation) and the total yield is reduced by 57 percent to 2 700 kg. This can be offset by increasing aeration (also simulated in POND), but with a corresponding increase in production costs: over USD800 if aerators are always running, about USD100 if switched on only at dusk whenever dissolved oxygen falls below 50 percent saturation.

The percentile 90 (P_{90}) for ammonia increases from 9.6 mmol/liter in the inflow to 88.2 mmol/liter in the pond, and the corresponding P_{90} data for chlorophyll are 8.3 and 40 mmol/liter, respectively (Figure 13). These values are in the ranges reported by Burford and Lorenzen (2004) for the late stages of giant tiger prawn (*Penaeus monodon*) culture in Australia (~1 mg/liter ammonia and 50–100 mg/liter chlorophyll). If water renewal is not used, NPP increases to 64 kg N and the chlorophyll P_{90} in the pond is 64.4 mg/liter, which corresponds to an ASSETS grade (Bricker, Ferreira and Simas, 2003) of hypereutrophic.

Future developments include the addition of stochastic functions to examine the relationship between stress (e.g. induced due to hypoxia), and the onset of diseases such as white spot syndrome (WSS) (Guan, Yu and Li, 2003).

Salient and emerging issues and the way forward

The final part of this review places virtual technology in the context of the Bangkok Declaration and ensuing developments, and discusses key aspects of the future of this technology in supporting decision-making for aquaculture in the coming years, in the context of EAA.

Implementation of the Bangkok Declaration

Background

The Conference on Aquaculture in the Third Millennium (the Bangkok Conference on Aquaculture) was held in February 2000 in Bangkok, Thailand, for the purpose of developing a strategy for aquaculture development in the next 20 years. It was attended by 549 participants representing all stakeholder groups in aquaculture, from more than 200 organizations and 66 countries in Asia, Africa, Latin America and the Caribbean, Europe, the former Soviet Republics, the Near East, North America and Oceania. The Conference crafted the document *Aquaculture Development Beyond 2000: the Bangkok Declaration and Strategy*, which has been published by the Network of Aquaculture Centres in Asia-Pacific and the Food and Agriculture Organization of the United Nations (NACA/FAO), and addresses the role of aquaculture in alleviating rural poverty, improving livelihoods and food security, and maintaining the integrity of natural and biological resources and the sustainability of the environment. The strategy comprises 17 elements that focus on measures that governments, the private sector and other concerned organizations can incorporate into their development programmes for the aquaculture sector. It highlights the need for regional and interregional cooperation to assist in its implementation (NACA/FAO, 2000).

Implementation

The Bangkok Declaration (NACA/FAO, 2000) aims to ensure the sustainable development of aquaculture over a ten-year horizon. The key elements of the Bangkok Declaration and Strategy have remained relevant and timely ten years after the issue of the document in 2000, but the diversity of the aquaculture sector has further increased since the conference took place in 2000. Of particular significance are the continuing advances in information and communications technology (ICT) which are giving a tremendous boost to the industry. None of the 17 strategic elements of the Bangkok Declaration made explicit reference to the use of virtual technology. since this area was only starting to emerge. However, it is clear that virtual technologies and decision-support tools for novel management are directly related to a number of strategic elements such as applying innovations in aquaculture, investing in research and development, and improving information flow and communication.

A number of specific actions and trends are proposed and discussed in the final part of this review, but in order to ensure that these technologies do not exacerbate the divide among nations, a brief overview of (i) constraints to application and (ii) success stories needs to be made.

Constraints in developing countries and actions needed

Prioritization

Aquaculture has special importance to developing countries, where it is not only critical in supporting healthy food provision for often large populations, but is also an important source of income for local communities. Developing countries often have a comparative advantage (as opposed to an absolute advantage) in aquaculture production, often due to climatic factors, i.e. it makes sense economically for resources to be utilized in aquaculture production because these nations can do this at a lower cost than developed countries. This may be of particular importance to developing countries, perhaps even more so than food provision and income, since these are consequences of economic incentives due to land availability, lower labour costs and favourable climatic conditions.

Which developing countries and which environments should be the priorities for the implementation of virtual technologies? From an EAA perspective, those making the most impact on the environment are the most likely candidates. One approach aimed at identifying such countries used FAO production statistics at country-environment level (freshwater, brackishwater and marine) to estimate the intensity at which aquaculture was practiced in each of those environments (Kapetsky, Aguilar-Manjarrez and Soto, 2010).

Which tools will be most appropriate to disseminate in a given country? A knowledge of the species being cultured can reveal the production systems and their associated kinds and magnitudes of impacts in a very general way. This review tabulates and illustrates many of the tools; thus, the approach outlined above can be refined to focus more closely on virtual technology needs by considering the potential impacts by species and culture systems in countries in which production data by species are reported.

Should dissemination of virtual technology tools be passive (e.g. packages freely accessible via the Internet) or active (e.g. training courses and workshops by region or by country)? Bearing on this decision, a fundamental question is: "What is the capacity (equipment, levels of technical competence) to responsibly and efficiently utilize the tools?"

In order to serve either of these avenues of dissemination, it is essential, above all, to establish the technical capacity, level of interest and financial commitment of the audience and the status of the Internet as a communications and data pipeline for technical support in each country. The focus should not be on developing countries alone for the reasons that: (i) virtual technology specialists in developed countries may be in a position to partner with FAO's Fisheries and Aquaculture Department's Aquaculture Service (FIRA) to aid dissemination; and (ii) companies established in developed countries often have aquaculture operations in developing countries, and could therefore also find it in their interest to offer support to virtual technology.

Application and challenges

Progress in the use of virtual technology in China, the world's largest aquaculture producer, illustrates some of these challenges. In recent years, continuing industrialization and population growth in the coastal areas of China have led to dramatic conflicts among aquaculture, industry, environment and human life, and the demand for sustainable aquaculture development and ICZM has become increasingly urgent.

Virtual technologies such as remote sensing and modelling for aquaculture management and ICZM were introduced to China during the late 1990s through a series of collaborative projects with Europe and North America. Knowledge transfer through these international programmes led to the application of some of the tools referred to previously, e.g. 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. However, most of the virtual technology applications for aquaculture management in China are still limited to the research technology development (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).

Conclusions

Virtual technologies have an important role to play through the use of (i) GIS, remote sensing and ecosystem-scale models to determine site suitability and carrying capacity; (ii) farm-scale tools to support licensing, EIA and optimization of production; or (iii) sensors for data acquisition for monitoring and modelling.

As illustrated by the case studies presented in this review, some of the key benefits of using virtual technology and decision-support tools for aquaculture management include: predictive capability and the ability to run "what-if" scenarios, simulation of environmental effects to quickly examine development scenarios, near real-time scenarios of environmental impacts of aquaculture at both the farm and bay scales, stakeholder consultation and participation for development of an efficient and auditable tool(s), integration of ecological and economic models to provide estimates of the medium to long-term profitability of IMTA, and use of dynamic models to simulate extreme events such as mortality due to oxygen stress in intertidal areas or excess biodeposition from a farm relative to natural sedimentation patterns.

A positive trend is that virtual applications for aquaculture are becoming broader in scope to the point that multiple issues are more frequently being addressed by any single application; for example, case studies illustrate the incorporation of multiple species and multiple models at different scales, including economic models, and varied temporal scales for the simulation of consequences of management options.

In the future, virtual technologies will play an increasingly important role in the prediction of potential aquaculture siting and production, environmental impacts and sustainability. The next decade will bring about major breakthroughs in key areas such as disease-related modelling, and witness a much broader use of virtual technology for improving and promoting sustainable aquaculture in many parts of the world. Even if attractive and promising, virtual technology requires adaptation to local conditions and compromises with respect to ease of use, data requirements and scientific complexity.

An enabling environment is crucial to link data/model requirements and current capacities (e.g. human resources, infrastructure, finances) for the development and/or use of virtual technologies at the national and/or regional level so that capacity-building activities can be initiated.

Summary of lessons learned and key recommendations

The aquaculture industry is going to be affected by many different issues and trends over the coming years, often operating concurrently, sometimes in unexpected ways, and producing changes in the industry that may be very rapid indeed: without a doubt virtual technology and decision-support tools will play an important role in addressing many of these, and will therefore underpin many elements of the *Bangkok Declaration and Strategy*. Some of the directions and challenges are listed below:

- Innovations will drive aquaculture development as new technologies such as virtual technologies become more widespread and aquaculture production becomes more and more competitive.
- Information exchange and networking are going to accelerate the use of virtual technology and decision-making for problem solving to support industry growth. Web-based access to real-time information will further accelerate this growth.
- Links between industry and research centers will need to be more effective to create a genuinely objective-led demand for virtual technology-driven RTD approach to sector development.
- There will be a need to strengthen collaboration among countries, mainly through educational and research programmes (e.g. interregional collaboration between Europe and developing countries).
- Strategic alliances will need to be reinforced or created for the implementation of virtual technology for aquaculture in developing countries; for example, FAO and WorldFish Center are working in many of the same target countries, and this could facilitate the transfer of research outcomes on virtual technology to end users. The same applies to collaborative research with third countries mediated e.g. by the EU, the United States of America and Canada.
- Many virtual technology tools will need to be more production and management-oriented; and even if attractive and promising, these tools will have to be adapted to local realities and conditions to really become useful (and used) in the future. This requires a compromise with respect to ease of use, data requirements and scientific complexity. Many such tools will evolve from service to product, requiring academic developers to accept a loss of control in conditions of application, as a natural trade-off (and inherent risk) of product maturity.

Finally, we provide some examples of key thematic and technical areas where virtual technologies for aquaculture are currently incipient, and expected to develop strongly in the next decade or so, integrating and complementing existing tools. This identification is based largely on gaps identified in this review.

Disease

Disease in cultivated species is a major source of concern, and is not as a rule predictable in the deterministic sense. A stochastic approach, based on risk and uncertainty analysis, will provide some measure of decision support, particularly where correlative approaches can be implemented, relating e.g. stress factors with disease outbreaks, such as reported by Guan, Yu and Li (2003) for WSS in penaeid shrimp. Statistical models based on the susceptible-infected-removed (i.e. recovered or dead) SIR approach (Anderson and May, 1979) have been used successfully to analyze furunculosis in chinook salmon (*Oncorhynchus tshawytcha*) (Ogut, Reno and Sampson 2004).

Only a few models have been developed to simulate pathogenic infections of shellfish with respect to physiology, e.g. Powell, Klinck and Hofmann (1996) for the American cupped oyster (*Crassostrea virginica*), but with widespread concerns about relaying, susceptibility and mortality, models focusing on a more mechanistic approach will undoubtedly appear over the next decade.

Risk assessments are under development for disease transmission in salmon aquaculture (mainly pancreas disease and salmon lice), based on hydrodynamics and risk of “water association” (e.g. the AquaStrøm project, developed by the Norsk Institutt for Vannforskning (NIVA, http://niva.no). Mechanisms such as pathogen survival and the role of vertical (vs horizontal) transmission are currently neglected, and thus in various respects this kind of work is at an early stage. The principle of zoning is currently a main management tool to establish “fire doors” to prevent or reduce the risk of infection among aquaculture areas.

Increasing emphasis is being placed on the use of real-time data acquisition combined with models for real-time analysis and short-term prediction of animal welfare, and it is expected that such systems will become cheaper and more generalized, and that some of the indicators and trends will find an application at longer time-scales, albeit by means of a probabilistic approach.

Other possibilities include the use of sentinel fish in the farmed population, fitted with real-time physiological sensors and data transmitters, as such technology becomes further miniaturized and increasingly cheaper (J. Bostock, personal communication, 2010).

Harmful algal blooms

This is another area where little predictive capacity exists, except in the short term through the use of operational oceanography, relying on bloom identification and tracking. Management is at present reactive, and modelling of appearance and development of such blooms is in its infancy, due to the lack of an appropriate paradigm. Sensors such as targeted RNA probes (e.g. Greenfield *et al*., 2006), integrating hand-held devices, or potentially deployed *in situ* and used in a networked framework will both help in early detection and management and contribute to the understanding of the underlying triggers. Considerable developments are also expected in remote sensing algorithms able to discriminate (at least) between HAB and non-toxic blooms (S. Bernard, personal communication, 2010).

Certification and traceability

The arrays of sensors that can be deployed at the farm scale to enable coupled monitoring and modelling, as exemplified in the Welfaremeter case study, additionally have an important role to play in both product certification and traceability. The number, reliability and accuracy of underwater sensors will increase and the cost will decrease, both with technological developments and market growth. Real-time data acquisition and interpretation will make it possible for consumers to visualize the whole "womb to tomb" cycle of an aquaculture product.

For instance, a batch of oysters may be "bar-coded" on a Website to reveal the origin of seed and the entire environmental interaction over the culture period, including metadata and measured data on water quality, HAB events, condition (meat ratio) of the animals, and impact on their environment, e.g. in terms of reduction of eutrophication symptoms through the indirect removal of nitrogen and phosphorus, and the addition of particulate organic material due to biodeposition. Such sensors will typically be queried at a subhourly frequency, particularly if they are also used for welfare monitoring; this will easily allow importers, health inspectors or consumers to perform verification and certification, and will provide an important contribution to both food safety and environmental awareness. For the farmer, the existence of this kind of integrated "taxi-meter" will also help improve various aspects of culture practice and increase attractiveness of the business model to the key sector of insurance. For the mainstream consumer, it is likely that such data will need to be presented in a comprehensible format, e.g. in the form of a few indicators.

Modelling with data scarcity

It is an axiom of modelling that good data are required to support acceptable predictions. The production of high-quality data, with appropriate spatial and temporal resolution, is expensive, and frequently beyond the scope of developing countries, except on a fairly limited scale. This, together with an often fragmented approach to the study of interacting ecosystems, in many cases driven by institutional barriers, makes model application a challenge.

The *deus ex machina* approach to monitoring, i.e. data for data's sake, without an underlying set of hypotheses, frequently means that scarce resources are under or mis-utilized, ignoring key scales, processes and variables.

Improved mechanisms for data access, particularly remotely sensed data, together with models that deal with uncertainty and risk, will both contribute to conversion of sparse data into more meaningful information – although such an approach may be considered inappropriate in parts of the developed world, in many countries it will be a much better basis for decisions than the options that are presently used. In addition, it will promote a "virtuous cycle" towards more informed decision support, the use of better data and more sophisticated virtual tools.

Information technology

The last five years have seen a huge leap in various areas of distributed computing, all of which are expected to develop significantly in the coming years. Three examples are presented here:

(i) The Web 2.0 phenomenon now provides a large diversity of community and corporation-based resources. This is exemplified on YouTube, where over 1 800 items currently exist for aquaculture, and around 20 for aquaculture modelling, including demonstrations of models such as Tropomod, developed by SAMS, Akvaplan-Niva, and partners from the Philippines for impact assessment of organic deposition (e.g. for tilapia ponds: www.youtube.com/watch?v=wwfqlueK3Kg).

(ii) There is a strong trend towards the development and use of software as a service (SAAS), as exemplified e.g. by Google Apps, which rival traditional desktop applications; this is incipient in the aquaculture world, but can be seen e.g. in the WinShell application (http://longline.co.uk/winshell), which allows users to simulate individual shellfish growth on line. Central to the development of this kind of application are rich Internet applications (RIA), which provide a full user experience and are an area of rapid growth (Anderson, McRee and Wilson, 2010).

(iii) Mobile computing is increasingly ubiquitous, and it is now possible to use GIS on many hand-held devices, as illustrated in Figure 14, which shows a large tilapia farm on Hai Ou (Seagull) Island on the Pearl River, China. The trend towards increasing use of such devices, including for various real-time applications in aquaculture management, will undoubtedly increase. In parallel, the concept of the stand-alone server is rapidly shifting towards cloud computing, which will tend to make the circulation of data both easier and cheaper. Both of these elements will contribute to bridge the gap between richer and poorer nations in the access to information technology.

FIGURE 14
Aquaculture (tilapia) geographic information system (GIS) displayed on a mobile platform (southern China)

Source: J.G. Ferreira, unpublished.

There is a need for tools and models that can forecast the future of aquaculture holistically, that is, with natural, socio-economic and administrative-policy realms integrated across temporal and spatial scales. This holistic approach can be implemented, but will require a commitment to well-coordinated multidisciplinary teamwork ranging from the global scale right down to the farm scale. As for many other areas of human endeavour, virtual technologies show enormous potential to inform and guide the future development of aquaculture towards a world which is more socially responsible, more equitable and more sustainable.

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