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

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Abstract

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

Introduction

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

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

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

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

Spatial tools in aquaculture from the view point of virtual technology

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

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

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

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

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

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

Functions and capabilities

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

Capacities

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

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

Advancing implementation

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

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

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

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

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

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

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

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

Broad-scale estimates of aquaculture potential

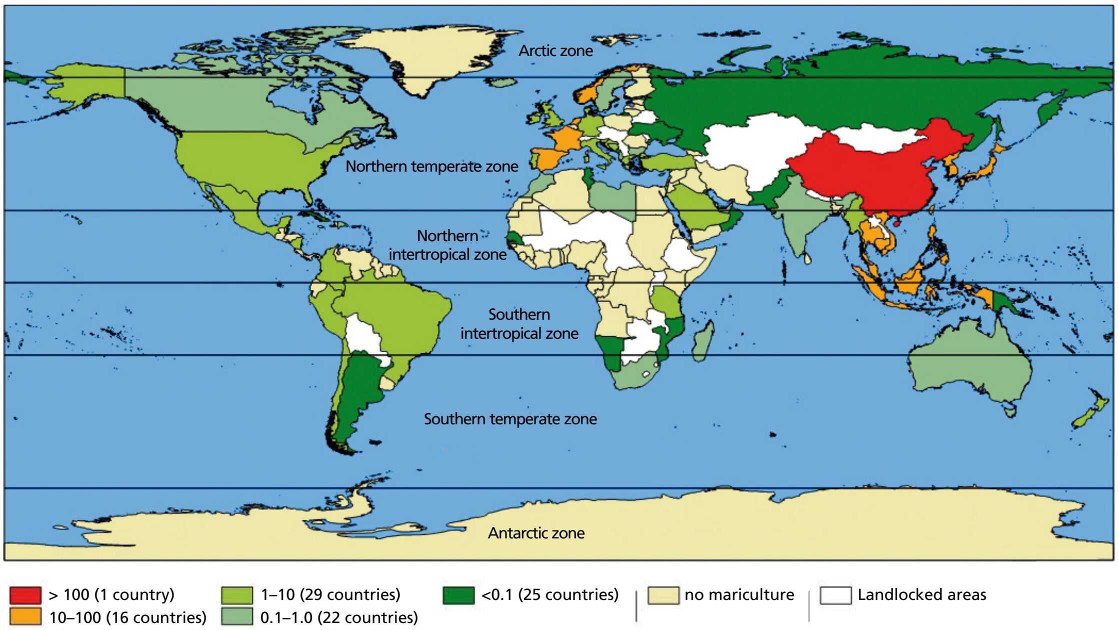
A definition of potential is "capable of development into actuality". In this sense the four activities-issues characterized (Table 1) are really one and the same, but compartmentalized in time and space for a better understanding of their respective roles. The purpose of this section is to advocate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

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

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

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

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



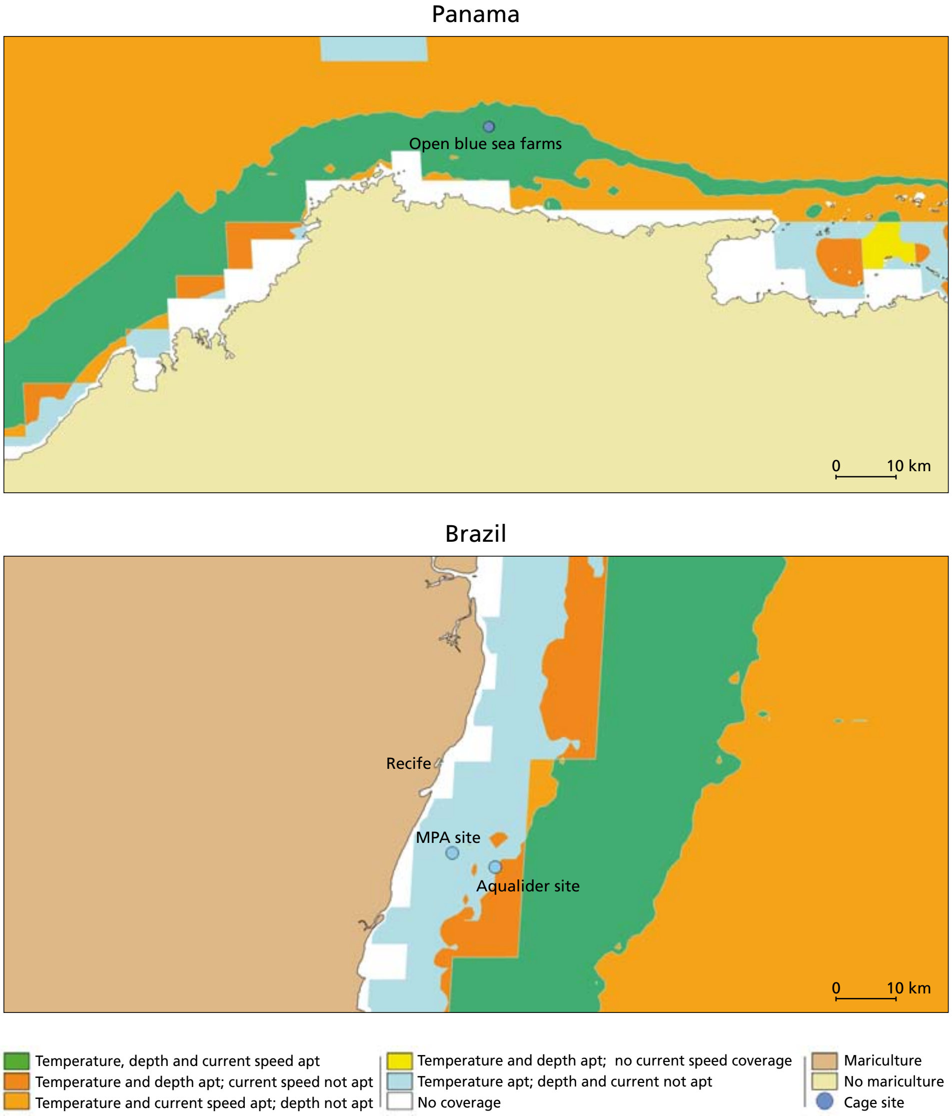
With regard to estimating potential, spatially defined frameworks are necessary for a common understanding of where and at what pace mariculture can develop. Frameworks can be rigid or flexible. Several rigid, single criterion frameworks –Exclusive Economic Zones, maritime claims and Off-of-the Coast and Offshore as defined by depth ranges – were considered, but found to not satisfy needs for estimating offshore mariculture potential. Rather, a pragmatic set of spatial frameworks, one for each species-culture system combination, that are flexible, integrate a variety of criteria fundamental to development, and that are based on the limits of current mariculture practice, was developed. The criteria included technical, economic, growth environment and other use considerations. In each framework there are three main considerations for estimating mariculture potential regardless of the size of the area under consideration or the location. They are (1) environments in which it is technically and economically feasible to place culture installations, (2) environments that promote favourable growth and high survival rates of cultured organisms and (3) locations which minimize competing and conflicting uses while taking advantage of possible complementary uses of adjacent space. The first consideration for mariculture development –technical and economic feasibility– was spatially integrated by identifying the coincidence of depths apt for submerged cages and longlines (25–100 m) along with current speeds apt for the former (10–100 cm/s) that are within a cost-effective limit of 25 nm (46.3 km) of a port, the later based on an economic study by Jin (2008). The cost-effective limit emphasizes the operational dependence of offshore culture installations on proximity to essential onshore facilities, goods and services as well as the travel time-distance to maintain economic viability of the operation. The second consideration for mariculture development –environments for favourable growth– was addressed by adopting temperature ranges based on mariculture practice for three species –cobia (*Rachycentron canadum*), 22 to 32 °C, Atlantic salmon (*Salmo salar*), 1.5 to 16 °C and blue mussel (*Mytilus edulis*), 2.5 to 19 °C, and for the latter, a filter feeder, chlorophyll-a >0.5 mg/m^3 was also used to define growth potential. These species are broadly indicative of mariculture potential in that together they span tropical to temperate climate zones, represent fed and extractive aquaculture. Further, they have well established culture systems and world markets. For the latter two potential was also estimated in integrated multiple trophic aquaculture (IMTA). In addition to mariculture, there is a host of potential competing and conflicting uses for the water surface, water column, bottom and sub-bottom even in offshore waters. The objective for mariculture development is to avoid or minimize these uses while taking advantage of uses that would be complementary. Marine Protected Areas (MPAs) were used to illustrate the effect on mariculture potential of possible competing and conflicting uses while taking advantage of possible complementary uses. Results were summarized by numbers of nations and aggregate surface areas meeting the criteria; however, the actual estimates were generated for each Exclusive Economic Zone of each sovereign maritime nation. Status and potential were also tabulated according to ranks of climate zones, and by first ranked maritime nations in each climate zone.

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

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

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

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



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

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

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

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

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

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

Siting aquaculture and zoning

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

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

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

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

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

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

Carrying capacity

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

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

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

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

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

Two other case studies are described here in somewhat more detail to give the scope and flavor of applied research that is on the way to becoming the widespread practical applications of the near future. With these criteria in mind, one of the most innovative and widely operational applications is AkaVis (Ervik *et al.*, 2008, Ervik *et al.*, forthcoming); described by Ferreira *et al.* (2012). It is an "all-in-one" Web-based interactive decision support system including site selection, carrying capacity and management monitoring modules. The interactive capability allows the users to immediately see the consequences of their choices. AkaVis combines a broad scale approach by covering the Kingdom of Norway's coastal aquaculture and multiple species by including the main fish and shellfish under culture. Moreover, it is holistic in EAA social terms by being designed for transparency, public participation and outside scrutiny. From a technical viewpoint, it is model driven on grids. The system integrates: (i) data regarding environmental parameters (ii) expertize (e.g. growth models, rules for weighting parameters and boundary values); (iii) legislation, regulations and directives (e.g. distance to other aquaculture sites); (iv) calculations, visualizations and interactivity with the user; and (v) basic and thematic maps.

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

Summary and conclusions

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

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

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

These conclusions were originally generated with the entire spectrum of spatial issues in aquaculture in mind; however, they pertain equally well to the more focused issues relating to potential, zoning, site selection and carrying capacity. From the perspective of functions and capabilities to deal with the general issues and those specific to this review, the power of spatial analysis is the ability to spatially define ecosystem boundaries where they do not already exist, to enhance existing ecosystem data with data specific to the needs of aquaculture, and then to integrate and analyze the environmental, administrative, social, and economic components of the ecosystem. The fact that spatial analytical capabilities can be employed at any scale from global to local means that the appropriate "scale" for spatial analyses in support of potential, zoning, siting and carrying capacity is defined by the boundaries of the problem expressed in ecosystem, economic, social and administrative terms.

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

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

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

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

Broad-scale estimates of aquaculture potential

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

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

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

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

Siting aquaculture and zoning

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

Carrying capacity

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

Main conclusions and recommendations

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

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

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

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