4. Estimating open ocean aquaculture potential in Exclusive Economic Zones with remote sensing and GIS: a reconnaissance

4.1 INTRODUCTION

In this section we address the question "Are there sufficient freely downloadable basic data available so that any country could assess its Open Ocean Aquaculture (OOA) potential at a reconnaissance level?" Our underlying objective is to encourage developing countries, particularly those presently with modest marine aquaculture production, to explore their own potential for marine aquaculture as part of the strategic planning process for sustainable aquaculture development.

4.2 MATERIALS AND METHODS

The GIS used in this study was Manifold (CDA International Ltd.), versions 6.0 and 6.5. Manifold was used because it is a very affordable (currently about one-fifth of the cost of the most widely used GIS software), but a fully functional GIS.

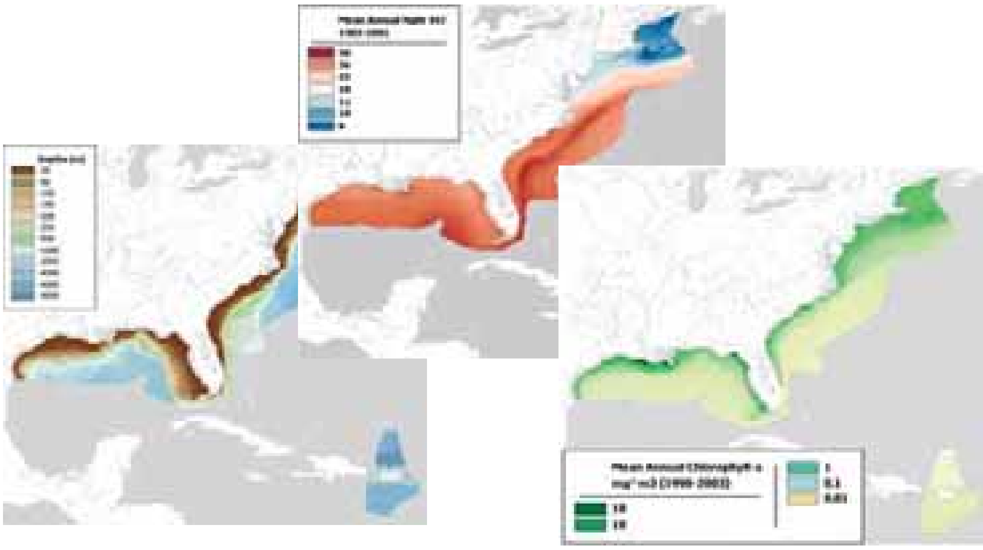
The United States of America was chosen as the target country for the study because the senior author resides there and because he has some familiarity with the offshore aquaculture issues at a national level and a first-hand knowledge of some of the coastal areas included in the study. A reconnaissance level study of open ocean aquaculture potential in the US EEZ is timely because an offshore aquaculture bill has recently been introduced to the US legislative branch.

Study area, indicator species and culture systems. Our objective was to estimate indicative aquaculture potential by selecting diverse environments, species, and culture structures. In this regard, our study area comprises the Atlantic, Gulf of Mexico and Puerto Rico-US Virgin Island (PR-USVI) EEZs. Thus, the study area, about 1.6 million km^2, is comprehensive of US territory on one coast and encompasses a very broad range of climatic and environmental conditions (Figure 4.1).

For realism and wide applicability, we selected species already being cultured in near shore US waters and that are cultured in other countries, as well. The cobia, *Rachycentron canadum*, is cultured in four countries and the total production in 2004 was about 20 000 tonnes. Cobia is a promising candidate for aquaculture because of its rapid growth rate, hardiness, and high quality of flesh. Cobia can grow to 4-6 kg in 1 yr (Arnold, Kaiser and Holt, 2002). The importance of the blue mussel is well established. It was cultured in 16 countries with an output of about 423 000 tonnes in 2004 (FAO 2006a). Additionally, we wanted to draw a contrast between the trophic levels of the organisms cultured, their temperature regimes, and culture systems. To this end, the cobia is a warm water fish and a top predator. It provides an example of "fed aquaculture" in that the cobia requires formulated feeds. In contrast, the blue mussel is a cold water, filter-feeding shellfish and in this latter regard provides an example of "extractive aquaculture". The former is cultured in cages and the latter using several types of suspended devices including longlines.

FIGURE 4.1
Study Area

FIGURE 4.2
Basic data: Bathymetry, SST and chlorophyll-a



GIS data

Spatial data for this study are in three components: (1) boundaries, (2) bathymetry and (3) SST and chlorophyll-a environments. EEZ data were readily available from the Office of Coast Survey (2006) however, data on state seaward boundaries, usually 3 miles (4.8 km), but sometimes 9 miles (14.5 km) had to be digitized for areas where the limits remain unresolved between states and the federal government.

Bathymetry (Figure 4.2) is from, the 2-minute resolution global relief data set, ETOPO2 (2001 version; National Geophysical Data Center, 2006). The data can be interactively downloaded with a choice of file formats for any geographic area desired via the National Geophysical Data Center Grid Translator (GEODAS) (2006).

The environmental data are SST and chlorophyll-a climatologies (Figure 4.2). The SST climatology has a resolution of 4 km and is based on data acquired at night from 1985 to 2001(National Oceanographic Data Center, NOAA (2005). The chlorophyll-a data resolution is approximately 9 km and the data are from 1998 to 2003 (National Oceanographic Data Center, NOAA (2004).

Thresholds

Thresholds relating temperature to growth were established for the cobia based on Ueng *et al*. (2001) and M.J. Osterling (personal communication, 2005). Ueng *et al*. (2001) state that cobia growth rates were highest from 28 to 32 °C and that growth decreased below 20 °C. They concluded that that half of the growth rate variation was from temperature variation. M.J. Osterling (personal communication, 2005) notes that he has raised cobia at temperatures from 21 to 28 °C and that better growth was attained at higher temperatures. He and others have observed that cobia "go off their feed" at temperatures below 20 °C. Accordingly, the thresholds were conservatively set as < 20 °C, no feeding; 20-25 °C, growth; >25 °C better growth. The spatial distribution of these conditions is shown in Figure 4.3.

Regarding, thresholds for the blue mussel relating temperature to growth Langan and Horton (2003) state that within a temperature range of 5-16 °C food quantity and quality are the most important factors affecting growth. Saxby (2002) made a world wide review of conditions at commercial bivalve culture sites among 10 countries. He concluded that temperature and food availability are the major factors affecting growth, and he also concluded that temperatures between 10 and 18 °C promoted good mussel growth. Newell (2001) stated that maximum temperature should be below 20 °C to prevent summer mortalities and he also indicated that blue mussels would survive and grow rapidly in some locations under 21.1 °C maximum summer temperature (Newell, 2003). The Island Institute (1999) produced a guide to blue mussel culture in Maine, the United States of America. It was found that temperatures from 4.4 °C to 21.1 are required for growth, but that at temperatures above 18.3 they begin to suffer mortality and lose byssal strength. Accordingly, the growth thresholds in relation to temperature were conservatively set at <4.4 °C, too cold for growth; 4.4 to 18.3 °C growth; >18.3 °C, too warm for growth and survival. The spatial distribution of these thresholds is shown in Figure 4.4.

Saxby (2002) found that mean chlorophyll-a concentrations of the order of 1-10 mg/m^3 were predominant at sites where bivalve growth did not appear to be greatly limited by lack of nutrients. Inglis (2000) reviewed carrying capacity of embayments in New Zealand for sustainable culture of the greenshell mussel, *Perna canaliculus*, a relative of the blue mussel, and developed "generic" guidelines for chlorophyll concentrations in relation to growth. He found that in concentrations less than 1 mg/m^3 growth was poor, but above that growth increased with increasing chlorophyll concentratioin up to 8 mg/m^3, above which it was uncertain whether growth would

FIGURE 4.3
Cobia growth and water temperature

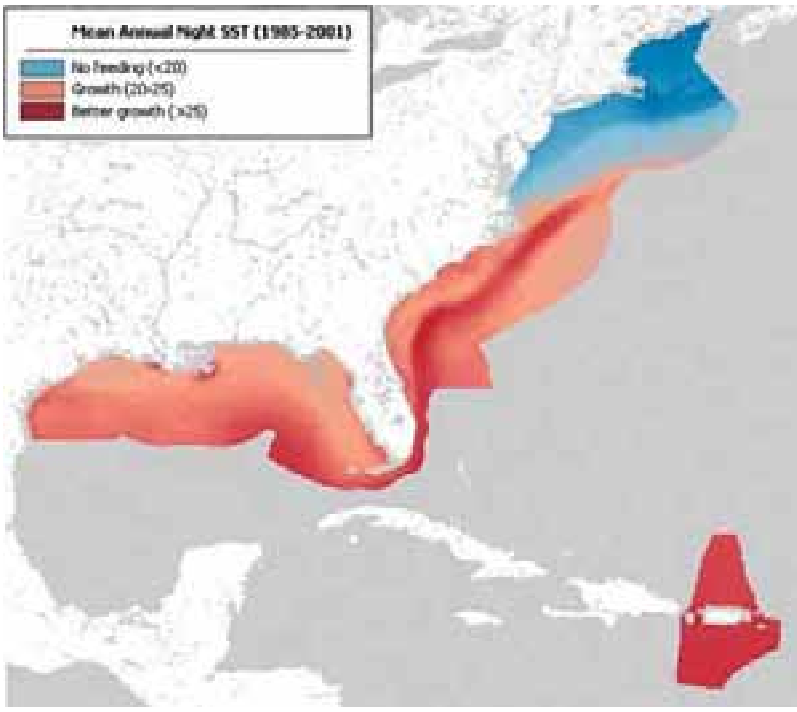


FIGURE 4.4
Blue mussel growth and water temperature

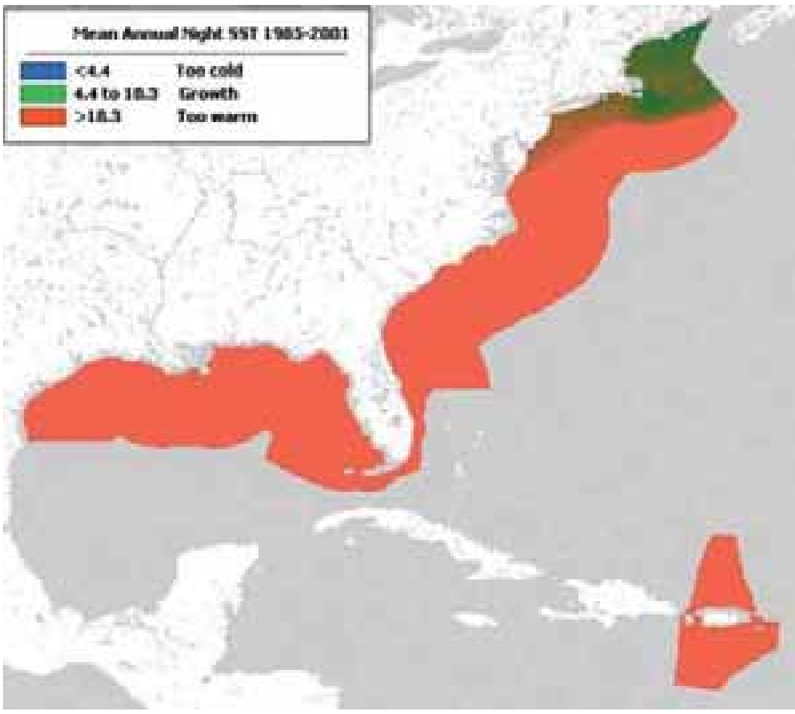


TABLE 4.1
Depth characteristics of experimental and commercial cage installations and specifications from manufacturers

Entity	Location	Cage type	Species	Depth at site (m)	Cage vertical depth (m)	Submersed depth from surface (m)	Apparent depth below cage (m)	Sources
Experimental and commercial installations								
Snapperfarm, Inc.	Puerto Rico, USA	SeaStation™ offshore submersible	Mutton Snapper (*Lutjanus analis*) and Culebran Cobia™ (*Rachycentron canadum*).	30	15	12	3	O'Hanlon *et al*, 2003 p. 263 in OOA ;http://www.snapperfarm.com/2006/aboutsnapperfarm.htm
Cates International	Hawaii, USA	SeaStation™ offshore submersible 3000	Pacific threadfin (*Polydactylus sexfilis*)	31	15	12	4	http://www.oceanicinstitute.org/_oldsite/techtransfer/seacage.html; Bybee and Bailey-Brock, 2003 p. 119 in OOA
Kona Blue Water Farms	Hawaii, USA	SeaStation™ offshore submersible 3000	Hawaian yellowtail (*Seriola rivoliana*)	61-67	20	6-9	32-41	http://seattlepi.nwsource.com/local/260433_kampachi22.html Kona Blue Water Farms (2003)
University of New Hampshire	New Hampshire, USA	Sea Station™ fish cage (SS600)	Atlantic halibut (*Hippoglossus hippoglossus*)	52				http://ooa.unh.edu/
Gulf of Mexico Offshore Aquaculture Constortium	Mississippi, USA	Sea Station™ fish cage 600 m3	Red drum (*Sciaenops ocellatus*)	25				http://www.masgc.org/oac/Phase%201%20RP1.pdf
SUBFlex, Ltd. (manufacturer)	Israel	Open Ocean Subflex submersable	N/A	60				http://www.subflex.org/
Specifications from manufacturers								
Ocean Spar LLC, (manufacturer)	Washington, USA	Sea Station fully submerged or floating	N/A	>25				http://www.oceanspar.com/files/OceanSpar_SeaStation.pdf
Farmocean International (manufacturer)	Sweden	Farmocean 4500	N/A	25		3		http://www.farmocean.se/General.pdf
Helgeland Holdings AS (manufacturer)	Norway	Polarcirkel Submersible	N/A			3-20		http://www.polarcirkel.no/gbframenedsenk1.htm
SUBFlex, Ltd. (manufacturer)	Israel	Open Ocean Subflex submersable	N/A	50-80	12			http://www.subflex.org/

FIGURE 4.5
Blue mussel growth and chlorophyll-a concentration

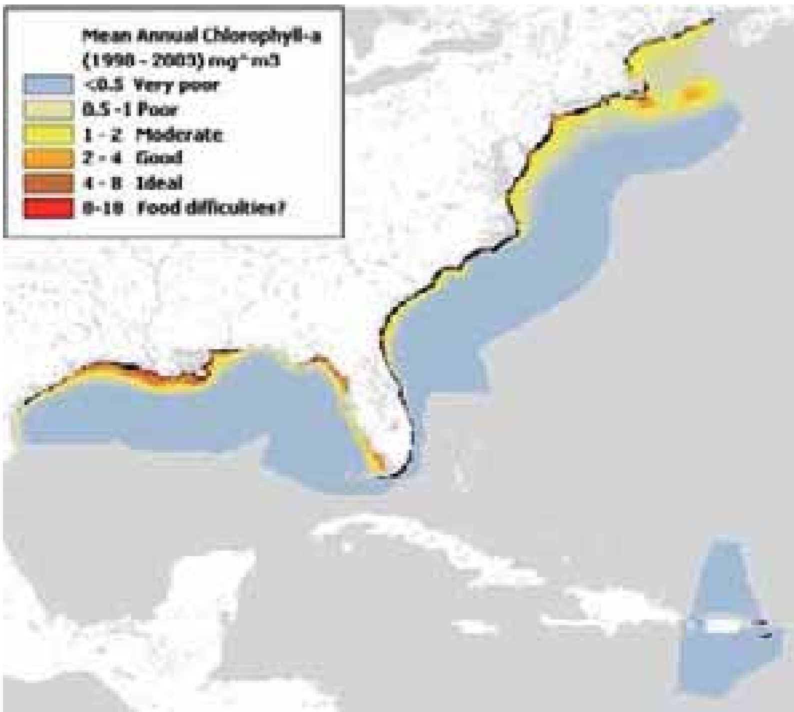
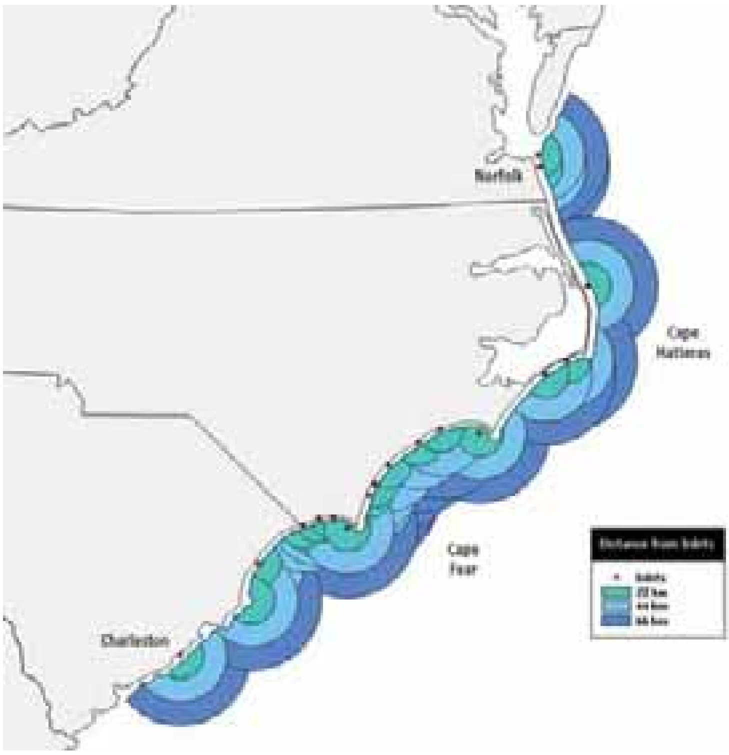


FIGURE 4.6
Access from inlets to the sea in 1, 2, and 3 hour one-way boat trips (22, 44, and 66 km)



continue to improve or would decrease due to food handling difficulties. The spatial distribution of thresholds relating mussel growth to chlorophyll-a concentration are shown in Figure 4.5; however, because of uncertainty of these thresholds for the blue mussel, the thresholds for the analyses were conservatively set at <1 mg/m^3, no growth; 1-8 mg/m^3, growth; >8 mg/m^3 possible difficulties with food handling.

Depth thresholds for cages were based on a review of current practice at experimental and commercial installations, and specifications given by cage manufacturers (Table 4.1). The minimum site depth found was 30 m, but one manufacturer recommends >25 m. Thus, a minimum depth of 25 m was established in order to avoid self-pollution under cages. The maximum depth found was 67 m. Although one manufacturer suggests that depths greater than 100 m would be possible, special moorings and anchoring would be required and these are still on the drawing boards. Additionally, inspection of mooring and anchoring structures in depths greater than 100 m would be tricky (Johan Obling, Farmocean International, personal communication, 2006). Thus, 100 m was set as a practical technological and economic limit of presently available cages. The University of New Hampshire (UNH) offshore mussel installation is at a depth of 40 m and the longlines are submersed to 12 m (CINEMAR, 2005). Thus, the -25 to -100 depth limits set for cages also approximate the depths that are suitable for structures to support mussel culture on submerged longlines.

Unthethered structures (free-floating or propelled cages) could occupy depths as shallow as the minimum cage depth, 25 m, and all deeper areas.

Access data

As pointed out in Section 1.4.1, access from a shore support facility to an offshore culture installation is an indispensable criterion for assessment of potential. A portion of the Atlantic coastline from southern Virginia near Norfolk to southern South Carolina near Charleston, about 700 km, was selected for analysis of time and distance from an inlet to the nearest area suitable for cobia culture. This stretch of the coast was selected because one of the authors lives in the approximate center and has first hand knowledge of some of the inlets. Furthermore, the digital nautical chart data were complete for this section of the coast. The chart data were important because the locations of inlets on nautical charts are signaled by "safe water" buoys that mark the seaward entrances to inlet channels. One-way service boat trips were set at 1, 2, and 3 hour (22, 44, and 66 km) ranges. These thresholds were based on the senior author's observation of the cruising speed of an approximately 11-meter long, fiberglass displacement hull, single screw, diesel-powered fishing boat (Figure 4.6). In contrast, Kite-Powell *et al*. (2003), used a much larger, somewhat slower boat in their bioeconomic model of finfish grow-out. The speed was 15 km/h and the payload capacity was 30 tonnes.

The above categories of data together with their corresponding thresholds are summarized in Table 4.2, and formed the basis of evaluating open ocean aquaculture potential in the United States of America (Atlantic, Gulf of Mexico and Puerto Rico –USVI EEZs).

GIS analyses

The analyses were basic to GIS and included importing, georegistering, cropping, surface contouring, buffering, overlaying and querying.

TABLE 4.2
Summary of thresholds used to evaluate open ocean aquaculture potential in USA (Atlantic, Gulf of Mexico and Puerto Rico –USVI EEZs)

Spatial Data and Source	Date	Resolution / Scale	Attribute data range	Thresholds
Mean Annual SST National Oceanographic Data Center, NOAA (2005) ftp://data.nodc.noaa.gov/pub/data.nodc/pathfinder/Version5.0_Climatologies/	1985-2001	4 km	6 – 30 °C	Cobia growth and water temperature: No feeding (<20) Growth (20-25) Better growth (>25) Blue mussel growth and water temperature: Too cold (< 4.4) Growth (4.4 to 18.3) Too warm (>18.3)
Mean Annual Chlorophyll-a National Oceanographic Data Center, NOAA (2005) ftp://data.nodc.noaa.gov/pub/data.nodc/pathfinder/CoralAtlas/	1998-2003	9 km	0.01 – 18 (mg ^m^{3})	Blue mussel growth and Chlorophyll-a concentration: No growth (< 1) Growth (1 - 8) Food handling difficulties possible (> 8)
Bathymetry ETOPO2 (2001 version; National Geophysical Data Center 2006) http://www.ngdc.noaa.gov/mgg/gdas/gd_designagrid.html	2001	2-min	-25 to – 8000 (m)	Cages for cobia and longlines for blue mussels Too shallow (< 25) Tethered and untethered structures (25 -100) Too deep for tethered structures; suitable for untethered structures (>100)
Access (Inlets) MapTech Chart Navigator and NOAA ENC Direct (2006) http://ocs-spatial.ncd.noaa.gov/encdirect/viewer.htm	Various	> 1:50 000	Virginia to South Carolina	Distances from inlets 22 km 1 hour one-way trip 44 km 2 hours one-way trip 66 km 3 hours one-way trip
Boundary Office of Coast Survey (2006) NOAA: http://chartmaker.ncd.noaa.gov/csdl/eez.htm	2006	N/A	US Exclusive Economic Zones for the Gulf of Mexico, Atlantic and Puerto Rico-US Virgin Islands	N/A

4.3 RESULTS

Depth and structures There is a narrow fringe in most places along the Gulf and Atlantic coasts that is too shallow for tethered structures such as cages and longlines (Figure 4.7). These make up 9% of the EEZ area. The adjacent seaward area, 19%, has depths suitable for tethered structures. There is a vast area, 72%, too deep for cages and longlines, where untethered (free or propelled floating farms) structures could be deployed. In contrast to the Gulf and Atlantic coasts, nearly all of the Puerto Rico – USVI area is too deep for tethered structures. Of course, untethered structures could also occupy the areas suitable for tethered structures.

Suitability for cobia Four classes of areas suitable for cobia culture and one unsuitable area have been defined based on growth and depth thresholds (Figure 4.8a and 4.8b). Despite the widespread favorable temperatures for cobia growth shown in Figure 4.3, only about 12% of the EEZ area would be suitable for tethered culture (i.e., anchored cages) when depth also is considered. Tethered cages are presently the only culture mode technologically available in depths less than 100 m. Much of the area that is suitable is not in close proximity to the shore.

FIGURE 4.7
Depth and suitability for culture structures

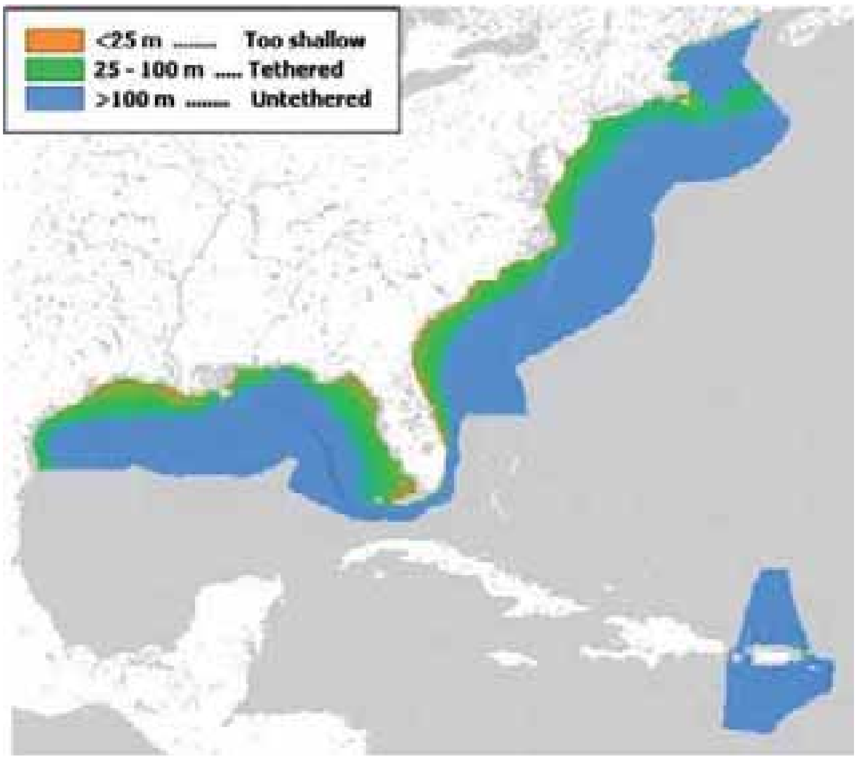


FIGURE 4.8A
Suitability for cobia culture in terms of culture structures and growth

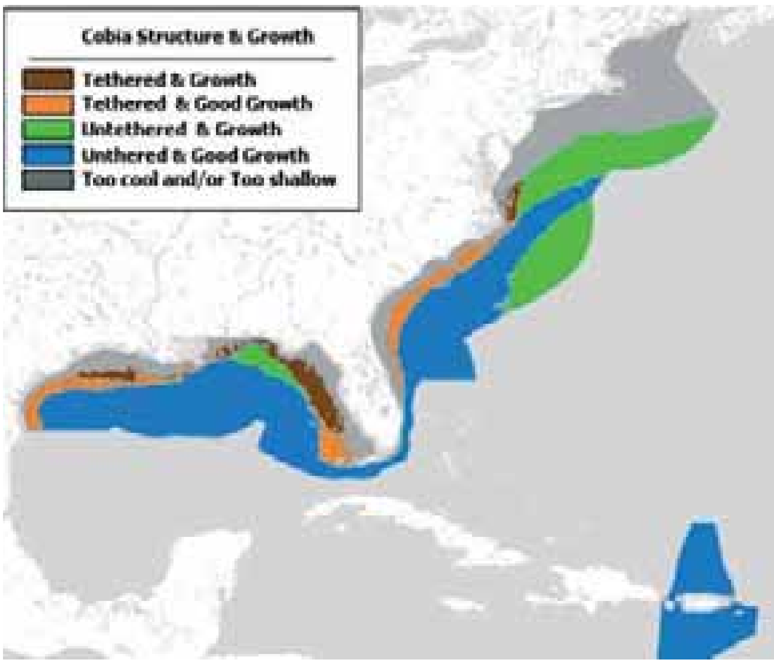


FIGURE 4.8B
Area-wise suitability for cobia culture (km²)

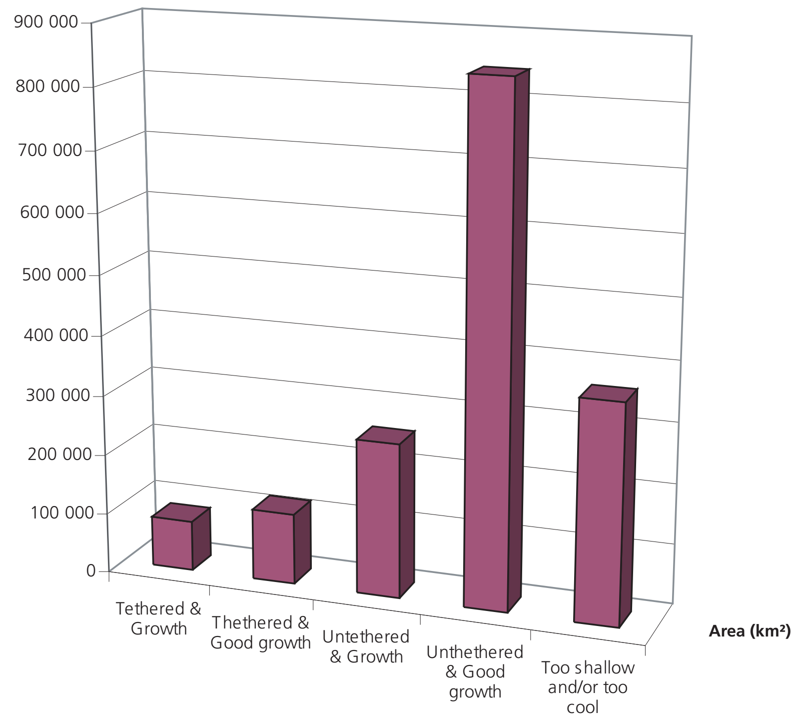
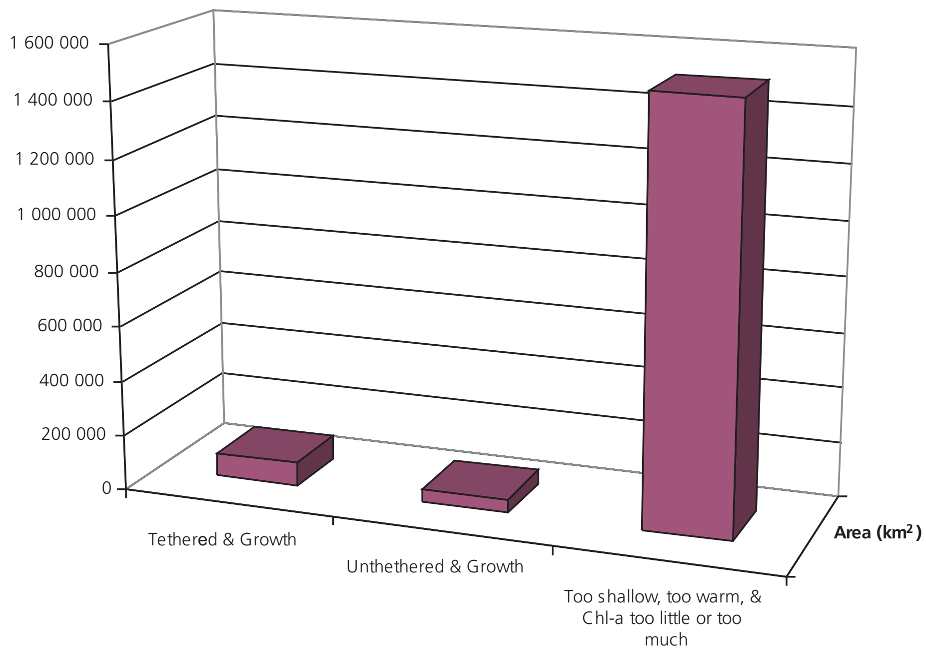


FIGURE 4.9A
Suitability for blue mussel culture in terms of temperature, chlorophyll-a concentration and depths

FIGURE 4.9B
Area-wise suitability for blue mussel culture (km²)



Suitability for blue mussel Taking into account blue mussel temperature-related growth (Figure 4.4), food availability in terms of chlorophyll-a concentration (Figure 4.5), as well as depths, only about 9% of the total EEZ area is suitable for blue mussel aquaculture on longlines, the available technology (Figure 4.9a and 4.9b).

Access Areas with different suitabilities for cobia culture are identified in relation to the three travel time-distance zones (Figure 4.10a and 4.10b). In summary, there are only a few inlets from which areas suitable for cobia culture are within 22 km (one hour) and these make up only 6% of the total area within the 22 km zones. Only 4 of the 17 inlets are within reach of suitable areas. The problem is not temperatures that are too cool. Rather, the depths are too shallow. As the depths increase the situation improves. At from 22 to 44 km from inlets, about 40% of the area is suitable and from 44 to 66 km the suitable area increases to 66% and suitable sites for aquaculture can be found associated with all the inlets. Not taken into account is that many of the inlets are not reliable, or inlets may not be close to the goods and services required of a marine aquaculture shore support facility.

4.4 DISCUSSION

Marine aquaculture potential for two "indicator" species has been shown in terms of surface areas of EEZs in which the species and culture systems could be established with present technologies and with depth-independent future technologies. Our results show, in a very general way, that temperatures in the Atlantic, Gulf of Mexico and PR-USVI EEZs favor the selection of plants and animals for culture that grow well in warm temperate and sub-tropical areas, that the bathymetry favors free-floating structures over anchored structures, and that the chlorophyll-a concentrations favor the culture of filter feeders only relatively close to shore. With particular respect to access, availability of inlets as well as time-distance from inlets to suitable sites could

FIGURE 4.10A
Suitability for cobia culture in terms of time-distance from an inlet

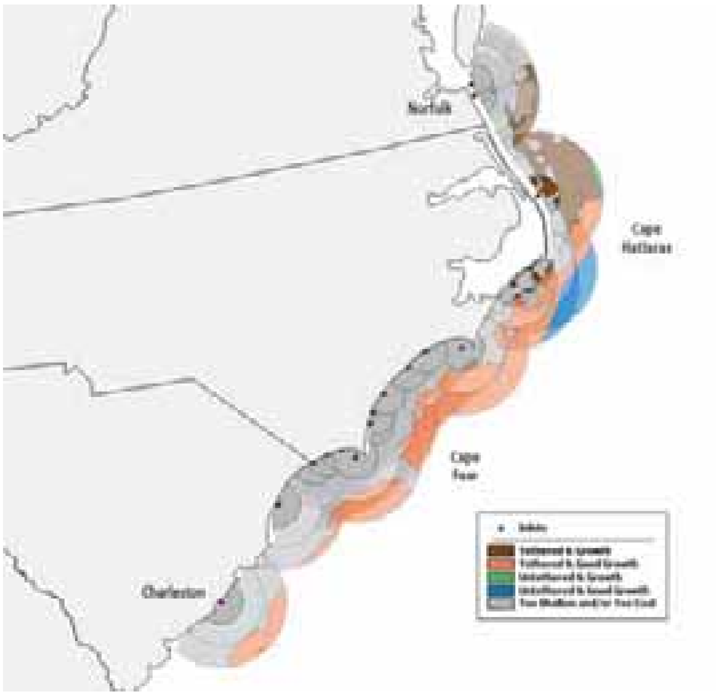
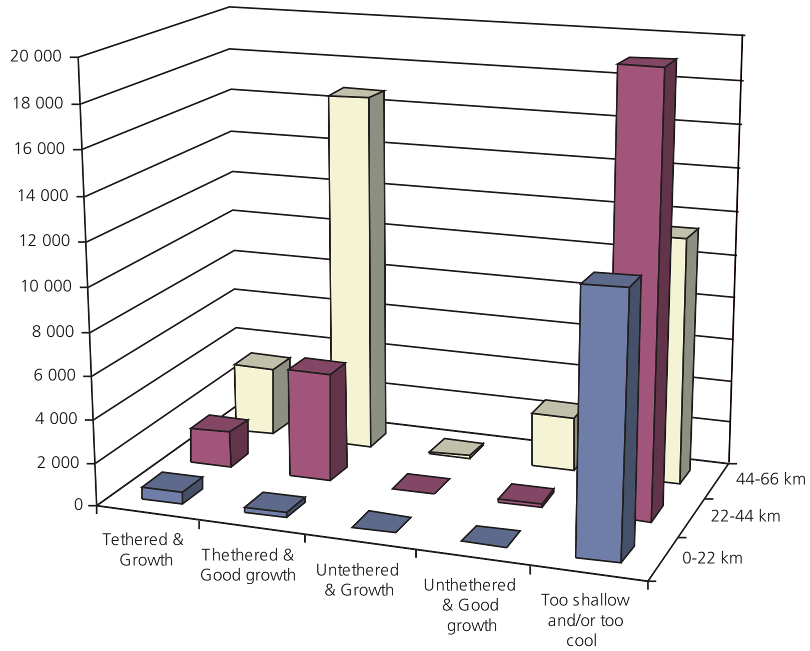


FIGURE 4.10B
Area-wise suitability for cobia culture in time-distance from an inlet



be important limiting factors on the development of OOA in the near future. More autonomous open ocean technologies will have to be devised to take full advantage of the vast EEZ areas available to most countries.

We have shown that it is possible to develop a useful reconnaissance-level GIS aimed at assessing open ocean aquaculture potential in an indicative way that is based on spatial data with a global extent that are readily available for download from the Internet. Because the spatial and attribute data are freely available, it should be possible to replicate our approach in any country by substituting the relevant species and culture systems for those used herein.

As our title indicates, this is a reconnaissance of aquaculture potential, not a definitive study. However, our results do point the way to several kinds of improvements that would result in better estimates of potential. One improvement would be to take into account additional production factors and constraints where the spatial data are available to do so. As an example, freely available GIS data, mainly from US government Internet sites, arranged according to where those data are to be applied – Culture structure; Shore support facility; Transport and maintenance trips - are assembled in Table 4.3. It can be seen that many varied and useful data are available; however, spatial continuity of the data remains a problem. In short, not all of the data are available for the entire coastline nor do they extend seaward to cover the entire EEZs. Nevertheless, it is encouraging that data are becoming more varied, that geographic coverage is growing wider and that the data are free to download.

The SST and chlorophyll-a climatologies that we used are averages over several years of data; however, in assessing potential, analysis of the extremes also is important as are seasonal and inter-annual variations. Thus, an additional improvement would be to analyze these data using shorter time intervals beginning with seasonal and monthly analyses. These results, in turn, could be used to identify areas and time periods where extreme conditions exist.

Implicit in our study is that the production factors –SST, bathymetry and chlorophyll-a – are of equal importance in estimating aquaculture potential. Clearly this is not the case. We have shown that access to the sea and distance from an inlet to an area suitable for culture can vary greatly. Studies carried out to estimate aquaculture potential for smaller areas at higher resolutions and that are more specific about culture systems and the culture environment can include weighting and ranking of production factors that marry GIS analyses with bioeconomic models.

It is noteworthy that two of three data sets, SST and chlorophyll-a, are based on remotely sensed data and the third set, bathymetry, is partly based on satellite altimetry.

The main problem was in finding sufficient reliable data to use to develop temperature and chlorophyll-a thresholds in relation to growth. One aspect is that different races of the same species may react differently to temperature so that results from one location may seem contradictory to those from another place. Another aspect is that temperature alone may not be the only determinant in actual culture operations. For example, cobia grows faster at the higher end of its temperature range, but may be more susceptible to some diseases in that part of the range, so, in practice, they may be raised at a less than optimum temperature for growth (M.J. Osterling, personal communication, 2005). Our thresholds were purposely kept rather broad firstly for simplicity of illustration and secondly because of some uncertainty in their reliability over the broad areas included in this study.

Finally, with only one open ocean location each for cobia and blue mussel culture near to our study area an attempt to verify our indicative estimates of potential would not have had any meaning.

TABLE 4.3
Freely downloadable spatial data and their application to assess marine aquaculture potential: cultured organisms (CO), offshore culture facilities (OF) and transport and maintenance trips from shore facilities to offshore culture facilities (TM)

Production factors	Application	Uniform Resource Locator (URL)
Bathymetry (depth & slope)	CO & OF	http://www.ngdc.noaa.gov/mgg/gdas/gd_designagrid.html
Bottom types	OF	http://www.csc.noaa.gov/opis/html/meta_lite/mseamap.htm
Chlorophyll-a	CO	ftp://data.nodc.noaa.gov/pub/data.nodc/pathfinder/CoralAtlas/
Coastal risk/vulnerability	SF, OF, TM	http://www.ncddc.noaa.gov/cra/gislibrary/
Coastal transport of organic and inorganic material	OF	http://www.nrl.navy.mil/content.php?P=03REVIEW199-2
County business patterns	SF	http://www.census.gov/epcd/cbp/view/cbpview.html
Current speed at 15 m depth	TM, OF & CO	http://oceancurrents.rsmas.miami.edu/atlantic/spaghetti-speed.html
Current speed at surface	OF & CO	http://www.aoml.noaa.gov/phod/dataphod/work/trinanes/INTERFACE/index.html
Dead zones	CO	http://serc.carleton.edu/images/microbelife/topics/map_of_gulf_of_.jpg
Fish spawning locations	OF	http://ocean.floridamarine.org/efh_coral/ims/viewer.htm
Fishing gears	OF & TM	http://ocean.floridamarine.org/efh_coral/ims/viewer.htm
Fish Processing facilities	SF	(should be among census data)
Harmful algal blooms	CO	http://www.ncddc.noaa.gov/habsos/Mapping/
Hurricane hazzard	TM, OF & CO	http://www.usgs.gov/hazards/hurricanes/
Inlet/outlet to sea	SF & TM	http://ocs-spatial.ncd.noaa.gov/encdirect/viewer.htm?
Major ports	SF & TM	http://www.csc.noaa.gov/opis/html/meta_lite/mports.htm
Marine protected areas	OF & TM	http://gis.mpa.gov/website/mma/viewer.htm
Marine offshore fish and shellfish distribution	OF	http://www.ncddc.noaa.gov/ecosystems/GISMapping/document_view
Minerals Management Services (MMS) Active and inactive oil and gas platforms	OF	http://www.gomr.mms.gov/homepg/pubinfo/repcat/arcinfo/index.html
Mixed layer depths	CO	http://www.nodc.noaa.gov/OC5/mixdoc.html
MMS uses outer Continental Shelf	OF & TM	http://www.mms.gov/ld/PDFs/atl-use.pdf
National highway planning network	SF	http://www.bts.gov/publications/north_american_transportation_atlas_data/
Population, business and geography centers	SF	http://quickfacts.census.gov/qfd/
Public use airports	SF	http://www.bts.gov/publications/north_american_transportation_atlas_data/
River plumes	CO	http://www.nrl.navy.mil/content.php?P=03REVIEW199-2
Sea surface temperature	CO	ftp://data.nodc.noaa.gov/pub/data.nodc/pathfinder/Version5.0_Climatologies
Species management zones	OF	http://ocean.floridamarine.org/efh_coral/ims/viewer.htm
Storm tracks	SF, OF ,TM	http://hurricane.csc.noaa.gov/hurricanes/download.html
Subsurface temperature	CO	http://las.pfeg.noaa.gov/las6_5/servlets/metadata?catitem=60
Time-distance to markets	SF	(should be among census data)

Production factors	Application	Uniform Resource Locator (URL)
Water port facilities	SF & TM	http://www.bts.gov/publications/north_american_transportation_atlas_data/
Wave height & Wind speed	SF, OF, TM	http://polar.ncep.noaa.gov/marine.meteorology/marine.winds/
Constraints		
Artificial reefs	OF	http://www.csc.noaa.gov/opis/html/meta_lite/martreef.htm
Coral HAPC	OF	http://www.nmfs.noaa.gov/gis/data/hapc.htm
Dredging disposal sites	OF	http://ocs-spatial.ncd.noaa.gov/encdirect/viewer.htm?
Essential fish habitats	OF	http://ocean.floridamarine.org/efh_coral/ims/viewer.htm
Marine protected areas	OF	http://www3.mpa.gov/exploreinv/explore.aspx
Marine sanctuaries	OF & TM	http://sanctuaries.noaa.gov/library/imast_gis.html
Military zones	OF & TM	http://ocs-spatial.ncd.noaa.gov/encdirect/viewer.htm?
Right whale critical habitat	OF	http://www.nmfs.noaa.gov/pr/pdfs/shipstrike/critical_habitat_traffic.pdf
Shipping lanes	OF	http://ocs-spatial.ncd.noaa.gov/encdirect/viewer.htm?
Wrecks	OF	http://ocs-spatial.ncd.noaa.gov/encdirect/viewer.htm?
Baseline data		
Coastline extractor	OF, SF, & TM	http://rimmer.ngdc.noaa.gov/coast/
Exclusive Economic Zones	OF	http://nauticalcharts.noaa.gov/csdl/EEZ.HTM
Maritime limits	OF	http://chartmaker.ncd.noaa.gov/csdl/mbound.htm
Mean high water shoreline	OF	http://www.nauticalcharts.noaa.gov/csdl/ctp/cm_vs.htm
Minerals management	OF	http://www.mms.gov/ld/atlantic.htm#SOBD
Nautical charts	OF, SF, & TM	http://www.nauticalcharts.noaa.gov/csdl/ctp/cm_vs.htm

5. Data availability

One of the first questions to be addressed when possible GIS and remote sensing marine aquaculture applications come to mind relates to data availability and quality. The kinds of data required necessarily depend on the application. The applications reviewed in Section 3 provide good sources from which lists of the data and data characteristics required for specific activities such as site selection and strategic planning can be assembled. Additionally, the study on aquaculture potential, Section 4, provides a list of data needs and sources for a marine aquaculture GIS data at national and sub-national levels. There are many overlaps in the kinds of data needed, but the differences will be evident in the resolution and the temporal and geographic distribution of the data.

Data availability for GIS can be considered in two realms: spatial data and attribute data. Spatial digital data can be viewed by broad use type. For example, there are shoreline data for base maps, and data layers to add to the base map such as bathymetry, temperature, and mineral claims. Acquiring data of a resolution appropriate for the study is an important consideration and often a challenge. For example, most of the data available for the open ocean are of too coarse resolution to be used for investigations of near shore aquaculture. There usually is a fairly close correlation between data resolution and extent of geographic coverage. Thus, data sets can be conveniently categorized as global, national, sub-national and local. Sub-national data sets usually pertain to first and second level administrative boundaries.

Attribute data are used to set thresholds on production factors. Two examples are (1) temperature thresholds relating to the growth rates of cultured organisms, and (2) thresholds relating to minimum and maximum depths for locating cages. Attribute data may take a long time to identify, compile and synthesize because of the need for extensive searches of the scientific literature and the Internet as well as for correspondence with experts.

Another important distinction is between data available to be freely downloaded from the Internet and commercially prepared data that must be purchased.

5.1 GEOGRAPHIC INFORMATION SYSTEMS DATA WITH A GLOBAL COVERAGE

Our emphasis is on global data, freely available via download from the Internet and that will support a first assessment of marine offshore aquaculture potential for any country as illustrated by the study of aquaculture potential (Section 4). In order to assess near shore aquaculture potential national and sub-national level data will be required. It is beyond the scope of this study to attempt to comprehensively compile national level data sets that could be employed for a marine aquaculture GIS; however, we do provide some examples of national level data that are readily available.

We make a distinction between two kinds of data (1) compilations of "static" data such as shorelines and climatologies, the latter usually based on relatively long streams of data, and (2) real-time, or near real time, data for aquaculture operations and management. It is worth noting that most of the data are based on various kinds of remote sensing.

Data compilations with a global marine reach include shorelines, bathymetry and climatologies of Sea Surface Temperature (SST) and chlorophyll at various resolutions and time intervals. Also included are compilations of remotely sensed data over land that can be useful for siting marine aquaculture shore support installations. The global data are briefly described below and summarized in Table 4.1, including the Uniform Resource Locator's (URLs) for downloads.

5.1.1 Geographic Information Systems data compilations

Shoreline data as a base map are important as a framework for all other layers. The World Vector Shoreline (WVS) is a digital data file containing the shorelines, international boundaries, and country names of the world. The WVS is divided into ten ocean basin area files. Together the ten files form a seamless world, with the exception of Central America, where there is an overlap between the Western North Atlantic file and the Eastern North Pacific file.

Bathymetry and elevation are available together in the 2-Minute Gridded Global Relief Data (ETOPO2). ETOPO2 is a compilation of several data sets and part of the data is based on satellite altimetry.

Useful climatologies, including SST, chlorophyll-a, Photosynthetically Active Radiation (PAR), wind speed, and oxygen concentration at 100 m, are provided for several averaging periods (e.g., monthly seasonal, annual) and at various resolutions. The SST climatologies are noteworthy in being provided for several additional averaging periods, including daily, 5-day (Pentad), 7-day (weekly), and 8-day and also because of the higher resolution, 4 km. In addition, each period is provided as daytime-only, nighttime-only, and day-night combined.

Although currents are among the most important data to assess marine aquaculture potential, current data are among the most difficult to realize at temporal and spatial resolutions that are useful globally, regionally and locally. A drifter-derived climatology of the world's near-surface currents has been assembled. A drifter is composed of a surface float which includes a transmitter to relay data, and a thermometer which reads temperature a few centimeters below the air/sea interface. The surface float is tethered to a subsurface float which minimizes rectification of surface wave motion. This in turn is tethered to a holey sock drogue, centered at 15 m depth. The resolution is only 1 degree x 1 degree. One version contains annual mean values of the near-surface currents and subskin sea surface temperature while another has monthly averages; however, it is available only for the tropical Atlantic.

Exclusive Economic Zone (EEZ) delineations are indispensable for the assessment of offshore aquaculture potential, particularly in areas that are disputed. Until recently the global data were commercial (i.e.Global Maritime Boundaries Database available from General Dynamics Advanced Information Systems at: http://www.gd-ais.com/capabilities/offerings/sr/gmbd.htm); However, the IOC's International Oceanographic Data and Information Exchange (IODE) through Flanders Marine Data and Information Centre has developed an open source version of EEZ GIS layer and is available for download at http://www.vliz.be/vmdcdata/marbound. Already used as part of GoogleEarth. It consists of lines features, with qualifiers describing meaning of these lines and why (i.e. sources) they were generated. The Flanders Institute will ensure maintenance of this EEZ GIS source. EEZ boundaries and accompanying area estimates can be viewed via the Sea Around Us Project (http://www.seaaroundus.org/eez/eez.aspx#).

Data useful for assessing potential for the development of shore facilities to support marine aquaculture include populated places, transportation systems (roads, railroads, airports), and administrative boundaries. Google Earth (http://earth.google.com/) offers the possibility of viewing and easily manipulating a satellite image backdrop at varying resolutions (generally 15 m, usually less than 3 years old) and acquiring such data for many areas of the world. An area of interest can be viewed, features of interest can be added, control points for georeferencing the selected area can be placed as needed, and the image can be exported in jpg format to make a simple map that can be georeferenced in a GIS to data from other sources. You can also use Keyhole Markup Language (KML), to share places and information with other users of Google Earth. Likewise, you can find KML files on the Google Earth Community site that describe interesting features and places.

Also potentially useful for the same purpose is the WMS Global Mosaic, a high resolution global image mosaic of the earth, produced from more than 8200 individual Landsat 7 scenes with a maximum resolution of 15 m.

The Munich Re Group provides NATHAN, a map with global coverage of natural hazards of obvious importance to marine aquaculture. The natural hazards include tsunamis, earthquakes, volcanic eruptions, storms, storm surges, tornados, hail storms, lightening, and sea ice. The hazard maps can be interactively viewed by zooming from global to sub-national levels on the Internet. The GIS data have to be purchased.

Harmful algal bloom maps already have been mentioned in Section 3.2. Some maps are available at regional levels. Global and regional maps could be useful, if the underlying data, including the causative organism, frequency of occurrence and precise locations can be obtained.

FAO and the United Nations World Food Programme (WFP), and more recently the United Nations Environment Programme (UNEP), have combined their research and mapping expertise to develop GeoNetwork opensource (http://www.fao.org/geonetwork/) as a common strategy to easily share geographically referenced thematic information between different FAO Units, other UN Agencies, NGOs and other institutions.

GeoNetwork opensource is a standardized and decentralized spatial information management environment, designed to enable access to geo-referenced databases, cartographic products and related metadata from a variety of sources, enhancing the spatial information exchange and sharing between organizations and their audience, using the capacities of the Internet. This approach of geographic information management aims at facilitating a wide community of spatial information users to have easy and timely access to available spatial data and to existing thematic maps that might support informed decision making.

The main goal of the GeoNetwork opensource software is to improve the accessibility of a wide variety of data, together with the associated information, at different scale and from multidisciplinary sources, organized and documented in a standard and consistent way.

The general kinds of data that can found in GeoNetwork that are relevant to marine aquaculture include: Administrative boundaries, coastlines, fishery resources distribution, fishing area locations, major cities, population density, roads, and watersheds.

The challenge is to enhance the data exchange and sharing between the organizations to avoid duplication, increase the cooperation and coordination of efforts in collecting data and make them available to benefit everybody, saving resources and at the same time preserving data and information ownership.

GeoNetwork opensource has been developed to connect spatial information communities and their data using a modern architecture, which is at the same time powerful and low cost, based on the principles of Free and Open Source Software (FOSS) and International and Open Standards for services and protocols.

An inventory and comparison of globally consistent geospatial databases and libraries has been compiled as an FAO publication by Dooley (2005). This publication presents an inventory of global data sources which can be used to provide consistent geospatial baselines for core framework data layers in the support of generalized base mapping, emergency preparedness, and response, food security and poverty mapping, and also includes data which is of relevance to marine aquaculture for both open ocean and shore support. In the publication, only globally consistent data sources at the scales of 1:5 million or larger for vector data and a nominal pixel size of 5 arc minutes or higher resolution for raster data, were considered. The sources of data presented in the inventory were identified based on a review of on-line Internet resources conducted in the first quarter of 2004 and updated in January 2005.

5.1.2 Real time remotely sensed data for operational management

The kinds of data pertinent to marine aquaculture that are acquired by satellite sensors include sea-surface temperature, oceanic-current patterns, formation of eddies and rings, upwelling, surface-wind action, wave motions, ocean color (in part indicative of phytoplankton concentrations), and sea ice status in the high latitudes (important for organisms, operations and structures).

Real time data, and more importantly predictions that can be made based on them, can be vital for the operational management of marine aquaculture installations. Real time remote sensing applications satisfy basic needs for management information. They are applications for the management of: (1) the cultured organisms, (2) the culture structures, and (3) access (sea and air communications) and shore support facilities. Data relating to the cultured organisms are temperature, chlorophyll-a, surface winds (wavelength, period, and height) and current speed. Data relating to the culture structures and access to it are current speed, wave height and wind velocity. These latter needs are largely satisfied by marine weather forecasts that are based on a combination of satellite remote sensing and data from fixed and free-floating sensors in the sea. Therefore, they are not dealt with in detail here and the focus is on data pertinent to the cultured organisms.

Looking to the future use of untethered (free floating) aquaculture installations on the open ocean, as described by Goudey (1998), current velocity is an important management variable in order to maintain the installation in locations that are the most favorable for the well-being of the organisms and for the safety of the installation itself with the least use of the supplemental propulsion system. On a longer time scale, knowledge of current patterns also is essential in order to predict optimum launching sites and to plan routes to achieve optimum environmental conditions. It is interesting to observe that the data required for these purposes are not raw, but already compiled or processed in some way through modelling or the combination of data from multiple sensors.

Chlorophyll-a

There are many opportunities to acquire chlorophyll-a data that have a global reach. An overview of the sources, characteristics, institutions involved is provided by the International Ocean Color Coordinating Group (http://www.ioccg.org/). As an example, the variety of products in terms of spatial and temporal resolution for only the MODIS Aqua sensor is shown by the NASA (USA) at http://oceancolor.gsfc.nasa.gov/PRODUCTS/L3_sst.html

Other real-time marine data

The Physical Oceanography Distributed Active Archive Center (NASA, USA) provides a single location from which data catalogs and downloads for a variety of global SST, current and waves data can be obtained (http://podaac.jpl.nasa.gov/catalog/). It is possible to subset, plot and view many of the data sets before downloading (http://poet.jpl.nasa.gov/).

5.2 NATIONAL DATA

A GIS aimed at near shore aquaculture potential will require data of higher resolution than those provided by the data sets with global coverage. Regional, national and local data sets will be of use. The reconnaissance study (Section 4) was created to illustrate a GIS to estimate marine aquaculture potential using a combination of global and nationally-available data sets.

In order to locate ocean-related data for other countries, the Global Change Master Directory (http://gcmd.nasa.gov/index.html), a directory to Earth science data and services, offers one opportunity. For example, this site can be used to identify national spatial data portals such as for India. Another approach is through Internet searches for national marine and oceanography center compilations (e.g., via the Open Directory Project http://dmoz.org/Science/Earth_Sciences/Oceanography/Data_and_Information_Resources/) or for specific countries.

The United States of America and Canada are world leaders in providing spatial data useful for the development and management of marine aquaculture although these data have not been made available specifically for this purpose. Some of the US data can be tailored as to geographic extent using Internet Map Server (IMS) technology and then downloaded with some choices of file format. An example of useful IMS data is the South Atlantic Habitat and Ecosystem IMS (http://ocean.floridamarine.org/efh_coral/ims/viewer.htm). GISFish includes links to sources of downloadable spatial data useful for aquaculture and fisheries.

6. Decision-making and modelling tools in GIS

6.1 INTRODUCTION

Fisher (in press) has looked at the evolution of GIS in fisheries applications apart from aquaculture. Although there is increasing sophistication in the use of GIS in fisheries, and as shown here, in marine aquaculture, too, there is an impression that the available modelling and decision-making tools are not being taken advantage of. Each of the commercial GIS packages has modelling and decision-making “built-in” to some extent.

For the purpose of this report, the terms “decision support tool” (DST) and “model” are defined as follows: A “DST” refers to an interactive, computer-based system that manipulates and presents spatial data to support informed, objective, and, in some cases, participatory decision making. A “model” is a simplified representation of reality used to simulate a process, understand a situation, predict an outcome, or analyse a problem. A model can be viewed as a selective approximation, which, by elimination of incidental detail, allows some fundamental aspects of the real world to appear or be tested (FAO 2006b).

The objective of this section is to provide an overview of the decision-making approaches and modelling tools used in selected applications of GIS to marine aquaculture. First, the basics of data classification and multi-criteria evaluation are presented. Following this, a description of the GIS-based models used for decision-making is provided; then an overview of GIS-Based decision support tools used for Marine Protected Areas is given together with a tabulated summary listing aquaculture issues that could be addressed using these tools. To sum-up this section an overview of DST used in selected applications of GIS to marine aquaculture is given.

6.2 CLASSIFICATION

Classification is an essential part of any data reduction process, whereby complex sets of observations are made understandable. It is almost always the case that the source data, whether in real or integer format, will need to be further classified before further use. Although any classification process involves some loss of information, a good scheme not only aims to minimize this loss, but by identifying natural groups that have common properties, provides a convenient means of information handling and transfer (Burrough, 1986). Furthermore, in any classification process, care must be taken to preserve the appropriate level of detail needed for sensible decision making at a later stage (Burrough, 1986; Aguilar-Manjarrez, 1996; Ross, 1998).

Aguilar-Manjarrez (1996) provides an exhaustive review of five methods that have been explored to classify data on land types for various uses that are equally relevant for classifying marine aquaculture data:

1. The FAO land evaluation methodology which assesses land suitability in terms of an attribute set corresponding to different activities.

2. The limitation method in which each land characteristic is evaluated on a relative scale of limitations.

3. The parametric method in which limitation levels for each characteristic are rated

on a scale of 0 to 1, from which a land index (%) is calculated as the product of the individual rating values of all characteristics.

4. The Boolean method which assumes that all questions related to land use suitability can be answered in a binary fashion, and that all important changes occur at a defined class boundary.

5. The fuzzy set method in which an explicit weight is used to assess the impact of each land characteristic. Fuzzy techniques are then used to combine the evaluation of each land characteristic into a final suitability index. Apart from a dominant suitability class, the fuzzy set method equally provides information on the extent to which a certain land unit belongs to each of the suitability classes discerned.

For GIS applications, any of the above methods can be used to classify source data into a four- or five-point scale of suitability (with one being the least suitable). However, the choice among classification methods is dependent on the type of data and intended uses of the output information. Classification allows normalization of all data layers, an essential pre-requisite for further modelling.

Fuzzy logic was applied to an inventory of aquaculture suitability in the Tiwi Islands, Australia (Field, 2001). Circumstances were that a substantial part of the coastline is Aboriginal land and the communities demand involvement in decisions for development. However, it was necessary for them to work in linguistic rather than mathematic terms. Also, it was recognized that conventional GIS based on sharply defined boundaries does not adequately reflect the actual situation of gradual transitions between areas of different suitabilities. A Team Approach Geographic Information System was created with four features (1) the use of linguistic terms in criteria evaluation rather than mathematical terms to define suitability, (2) semi-automatic pair-wise comparisons to estimate weights on criteria in Microsoft Excel, (3) application of a visual modelling environment in ModelBuilder (extension of ESRI Spatial Analyst 2.0), and (4) the final GIS running on Arc/View software.

The general approach was to define thresholds for criteria, to rate the thresholds in numerical and linguistic terms (e.g., a range in slope of 4-5 degrees is assigned a rating of one with an equivalent linguistic description of "very low" for suitability. The corresponding fuzzy number series in four sets is 0.0, 0.0, 0.1, 0.2. The two 0.0 values in different categories demonstrate that there are no sharp boundaries between slopes of different suitabilities. This approach, when all of the criteria are considered in the four fuzzy number sets, results in four maps ranging from the most stringent to the least stringent. Stated differently, four different interpretations of the same criteria statements result in four maps of suitability.

6.3 MULTI-CRITERIA EVALUATION

Complexities in development planning and management for marine aquaculture can be difficult without the aid of decision making-aids such as multi-criteria decision making. However, their use in marine aquaculture is limited. Many of the development and managerial issues of marine aquaculture have underlying geographic or spatial contexts, so there is considerable potential for using GIS.

GIS has considerable potential for both policy decisions and resource allocation decisions. Policy decisions are intended to influence the decision behaviour of decision makers whilst resource allocation decisions involve decisions that directly affect the utilization of resources.

GIS for policy decisions also has potential (almost unrealized at this time) as a process modelling tool, in which the spatial effects of predicted decision behaviour might be simulated. Simulation modelling, particularly those that incorporate socio-economic issues are still in their infancy. However, it is to be expected that GIS will play an increasingly important role in this area in the future.

Resource allocation decisions are also prime candidates for analysis with a GIS. Land evaluation and allocation is one of the most fundamental activities of resource development. However, without procedures and tools for the development of decision rules and the predictive modelling of expected outcomes, this opportunity will largely go unrealized.

GIS-based Multi-Criteria Evaluation (MCE) involves the utilization of geographical data, the decision maker's preferences and the combination of the data and preferences according to specified decision rules. Over the last decade, a number of multi-criteria methods have been implemented in the GIS environment including: weighted linear combination (WLC), ideal point methods, concordance analysis, Analytical Hierarchy Process (AHP), Analytical Network Process (ANP), and the Order Weighted Average (OWA). Among these procedures, the WLC and Boolean overlay operation are considered the most straightforward and have traditionally dominated the use of GIS as decision support tools (Malczewski, 1999; Malczewski; 2006).

In the WLC criteria are standardized to a common numeric range, and then combined by means of a weighted average. The result of a WLC is a map of suitability that may then be masked by one or more constraints and finally thresholded to yield a final decision. In the Boolean procedure all criteria are reduced to logical statements of suitability and then combined by means of one or more logical operators such as intersection (AND) and union (OR).

The Order Weighted Averaging (OWA) module provides an interesting alternative to the commonly-used linear weighted combination approach to aggregation of multiple criteria. By varying the importance of the factors in particular order positions, one can adjust the levels of tradeoff between factors and risk aversion in the solution incorporated into the final model. Malczewski (2006) presents an interesting implementation of the OWA approach as a platform for integrating multi-criteria decision analysis and GIS to a real-world environmental management problem that involved developing management strategies in the Cedar Creek watersheds in Ontario, Canada.

6.4 MODELLING

Multi-criteria evaluation decision-making models

A comprehensive review on "GIS and Multi-criteria Decision Analysis' is provided by Malczewski (1999). The emphasis of Malczewski's review is on GIS-based modelling of spatial multi-criteria problems, with a primary goal being to "introduce the readers to the principles of spatial multi-criteria decision analysis and the use of multi-criteria decision techniques in GIS environments". The text of this review is organized as follows: Chapter 1: Geographical data, information, and decision-making; Chapter 2: Introduction to GIS; Chapter 3: Introduction to multi-criteria decision analysis; Chapter 4: Evaluation criteria; Chapter 5: Decision alternatives and constraints; Chapter 6: Criterion weighting; Chapter 7: Decision rules; Chapter 8: Sensitivity analysis; Chapter 9: Spatial decision support systems; and Chapter 10: Multi-criteria-Spatial decision support systems case studies. The structure of the text and ordering is logical. The intended audience is GIS and decision analysts and both undergraduate and graduate students in applied GIS, quantitative analysis, and spatial decision support systems courses. Malczewski notes that the text assumes that the reader has limited mathematical background. Rather than derive formulations and formalize solution techniques, the text identifies associated software packages that may be utilized.

Nath *et al*. (2000), in the context of applications of GIS for spatial decision support in aquaculture, identified constraints on the implementation of GIS and proposed a seven-stage, user-driven framework to develop a GIS including personnel, activities and analytical procedures. Nath's review remains relevant as a background document on multiple criteria evaluation (MCE) basics for aquaculture.

A number of publications that have been produced at the Institute of Aquaculture (http://www.aquaculture.stir.ac.uk/GISAP/gis-group/) have focused on the construction of "Hierarchical models" (Aguilar-Manjarrez, 1992; Aguilar-Manjarrez 1996; Salam, 2000; Pérez, 2003; and Scott, 2004) for strategic planning of aquaculture development using MCE. In this approach, naturally grouped variables are first considered together to produce 'sub-model' outcomes such as water needs, soil suitability, input availability, farm gate sales, and markets. It is often the case that a source variable or processed layer will be used in more than one sub-model and that the layer may need to be transformed depending on the intended purpose. Each of these sub-models may, in turn, be derived from lower-level models which pre-process variable data into useful factors. Once the variables (i.e. production functions and constraints) are organized into sub-models weights are derived for each sub-model and then combined in rank order using the MCE technique.

Multi-criteria decision making models (MCDM) can be very useful to support decision making, however, there is not much done in aquaculture. While MCDM have been widely used for agricultural operational as well as strategic planning purposes, only a handful of applications to aquaculture were found in the literature: Sylvia and Anderson (1993) describe an economic policy model for net-pen salmon farming; Martinez-Cordero and Leung (2004) present a MCDM developed for the purpose of evaluating the sustainable development of shrimp farming in northwest Mexico, and El-Gayar and Leung (2006) developed a MCDM framework for the planning of regional aquaculture development.

Marine data model

The ArcGIS Marine Data Model represents a new approach to spatial modelling via improved integration of many important features of the ocean realm, both natural and manmade. The goal is to provide more accurate representations of location and spatial extent, along with a means for conducting more complex spatial analyses of marine and coastal data by capturing the behaviour of real-world objects in a geodatabase. The model also considers how marine and coastal data might be more effectively integrated in 3-D space and time. Although currently limited to 2-D, the model includes "placeholders" meant to represent the fluidity of ocean data and processes (http://dusk2.geo.orst.edu/djl/arcgis/about.html)

Commercial models for aquaculture

AquaModel is an information system to assess the operations and impacts of fish farms in both water column and benthic environments, the first of its kind. AquaModel is a "plug-in" model that resides within the EASy Marine Geographic Information System which has been used on numerous studies and investigations involving fisheries and oceanographic topics. All environmental information from field measurements to satellite imagery is readily available for model development and use. AquaModel can be used to examine near and far field effects of individual or clusters of farms in the coastal shelf where nearshore or open-ocean aquaculture may develop. It is being adapted to deal with multiple, separate cages and multiple farm sites to meet this challenge. AquaModel is designed for: Administrators, who establish and enforce rules and extent of impact; Fish farmers, who wish to plan farms and obtain permits and; Investors, who wish to assess risks and opportunities (http://netviewer.usc.edu/aquamodel/Overview.html).

6.5 DECISION SUPPORT TOOLS

Software for decision-making

Belton and Stewart (2002) state that software is essential for effective multi-criteria analysis. In this way the facilitator, analyst and decision-maker are free from the technical implementation details and are able to focus on the fundamental value judgment and choices. They conclude that although it is possible to set-up macros in a spreadsheet to achieve this, it is more convenient to use specially designed software.

Table 6.1 shows a list of software tools compiled by Janssen and van Herwijnen (2006) to support multi-criteria analysis that may aid marine aquaculture activities (siting, zoning, monitoring, etc). The list becomes rapidly outdated. Therefore, other listings of MCE software can be found in Belton and Stewart (2002) and at http://www.lionhrtpub.com/orms/surveys/das/das-html.

TABLE 6.1
Software to support multi-criteria analysis (updated from Janssen and van Herwijnen, 2006)

Package	Short description
Problem structuring for discrete choice problems	
Decision Explorer 3.2	Qualitative data analysis, linking concepts through cognitive or cause maps(http://www.banxia.com)
Mind Manager 4.0	Structures complex situations through organizing ideas and concepts, graphical visualization with icons, graphics, colors and multimedia (http://ww.mind-map.com)
Discrete choice problems	
Criterium Decision Plus 3.0	Value function model based on trade-off analysis (http://www.infoharvest.com)
DEFINITE 3.1	Multiattribute value functions including option for imprecise preference information, cost-benefit analysis, outranking. (http://www.definite-bosda.nl)
HIPRE	Multiattribute value functions with imprecise preference information (http://www.hipre.hut.fi)
Hiview	Multiattribute value functions (www.enterprise-lse.co.uk)
Logical Decisions 5.1	Multiattribute value functions and the analytical hierarchy process (AHP) (http://www.logicaldecisions.com)
VISA	Multiattribute value functions graphical interaction and presentation (http://www.simu18.com/visa.htm)
Discrete group choice problems	
Team Expert Choice	AHP, pairwise comparisons (http://www.expertchoice.com)
Super Decisions Software	ANP, analytical network process (http://www.superdecisions.com/index_tables.php3)
VISA Groupware	Multiattribute value functions (http://www.simu18.com/visa.htm)
Web-HIPRE	Multiattribute value functions and AHP (http://www.hipre.hut.fi)
Discrete spatial choice problems	
Idrisi 32	A GIS that includes the following decision support procedures: WEIGHT (AHP), MCE (Boolean combination, weighted linear combination or ordered weighted average), RANK (rank order the cells), MOLA (allocate pixels to multiple objectives), and OWA (provides ordered weighted average of factors to adjust the level of tradeoff between factors and risk adversion) (http://www.clarklabs.org/).
EMDS	Ecosystem management decision support; combines ArcGISTM, NetWeaver and Criterium DecisionPlus (http://www.fsl.orst.edu/emds)

Based within the Graduate School of Geography at Clark University, Clark Labs is known for pioneering advancements in decision support. Clark Labs is best known for its flagship product, the IDRISI GIS and Image Processing software. Over the past several years, the research staff at the Clark Labs have been specifically concerned with the use of GIS as a direct extension of the human decision making process—most particularly in the context of resource allocation decisions. In 1993, IDRISI introduced the first instance of Multi-Criteria and Multi-Objective decision making tools in GIS. To date, IDRISI is still the industry leader for the development of decision support software.

Another noteworthy software is DEFINITE. The software is novel for two main reasons; first because it is not designed around one multi-criteria technique like most software packages, on the contrary, it is toolbox, and second because it is visual and interactive and facilitates communication about the problem and the evaluation of results. Janssen and van Herwijnen (2006) describe the characteristics of this tool.

The Super Decisions software is used for decision-making, and it implements the Analytic Network Process (ANP) developed by Saaty (2006). The program was written by the ANP Team, working for the Creative Decisions Foundation. The ANP is an essential tool for articulating our understanding of a decision problem. It is a process that allows one to include all the factors and criteria, tangible and intangible that have a bearing on making a best decision.

The ANP, provides a way to input judgments and measurements to derive ratio scale priorities for the distribution of influence among the factors and groups of factors in the decision. Because the process is based on deriving ratio scale measurements, it can be used to allocate resources according to their ratio-scale priorities. The well-known decision theory, the Analytic Hierarchy Process (AHP) (Saaty, 1980) is a special case of the ANP. Both the AHP and the ANP derive ratio scale priorities for elements and clusters of elements by making paired comparisons of elements on a common property or criterion. Although many decision problems are best studied through the ANP, one may wish to compare the results obtained with it to those obtained using the AHP or any other decision approach with respect to the time it took to obtain the results, the effort involved in making the judgments, and the relevance and accuracy of the results.

The ANP has been applied to a large variety of decisions: marketing, medical, political, social, forecasting and prediction and many others. Its accuracy of prediction is impressive in applications that have been made to economic trends, sports and other events for which the outcome later became known. Detailed case studies of applications are included in the ANP software manual and in the book; "The Analytic Network Process: Decision Making with Dependence and Feedback" by Saaty (2006).

Decision-support Tools for Marine Protected Areas (MPAs)

To manage the complex issues affecting MPAs, managers often turn to technology for help in understanding and analyzing the resources and environments of their MPAs. MPA managers and scientists are increasingly using GIS and remote sensing to map and analyze the resources under their jurisdiction.

In an effort to document existing GIS decision-support tools to aid MPA managers, the MPA Center and the NOAA Coastal Services Center compiled an "Inventory of GIS-Based Decision-Support Tools for MPAs (Pattison, dos Reis and Hamilton, 2004) . The aim of this inventory is to make the MPA community aware of existing GIS-based decision-support tools that may aid them in a variety of MPA-related activities (siting, zoning, monitoring, etc). The tools highlighted in this inventory provide functionality ranging from visualizing and integrating oceanographic data to site suitability modelling and incorporating stakeholder input. Custom made GIS-based tools mainly include ArcView 3x extensions, and other tools/software are CI-SSAT, EwE, GiDSS, HSM, OCEAN, MARXAN, e-Site, Sites v1.0, and CARIS GIS and CARIS LOTS (Table 6.2). Some of these tools were designed with customized algorithms to produce habitat suitability maps, select planning unit's reserve siting, or to establish marine reserve networks. Many tools are adaptable to any location provided the appropriate site-specific data layers are available and most tools are freely available for download. Of interest is the incorporation of socio-economic data in many of the tools and that two of these tools (i.e. Great Barrier Reef Marine Park's Representative Areas Program (RAP) and EcoTrust's Use of OceanMap) have been used in actual zoning and monitoring activities.

Some tools demonstrate a process for incorporating local knowledge into decision-making, which adds an important participatory component for stakeholders and yields significant information. Interactive mapping sites include "GiDSS" where users will be able to specify their particular problem or issue, and the tool, using a herring-bone decision tree, will return suggested data layers related to the issue, and "e-Site' an on-line geographic information system that enhances the involvement of stakeholders in the public participation processes of site selection issues in the marine environment.

Notably the only decision support tool that included aquaculture was the study by O'Donnell, Cronin, and Cummins on "Sustainable coastal habitats: GIS tools for effective decision support". Despite this, our impression is that these tools for MPAs could also be used in marine aquaculture to address aquaculture issues as illustrated in Table 6.2.

Each tool summary includes a description of what the tool does, the data and software needed to run it, and contact information. The references and specific project descriptions in this inventory give additional technical background and illustrate how these spatial tools can be used in conjunction with other mechanisms to facilitate MPA related management decisions.

Because new tools and techniques will invariably be developed and improved upon, it is the intent of MPA staff to maintain this inventory as a living document. As such, the inventory will be updated on a regular basis to reflect these changes and will be available in hard copy or online at http://www.mpa.gov. The MPA community are encouraged to alert MPA staff to any tools, projects, or papers that would be appropriate for future inclusion.

Selected applications of GIS to marine aquaculture

The general approach used in the GIS application reviews presented in Section 3, included a classification phase to define thresholds for each factor to cast them into suitability classes for further modelling.

Decision support amongst reviews of marine cage aquaculture applications mainly included the integration of expert opinion using MCE techniques, which occasionally included field verification and/or estimates of carrying capacity or productivity. Only two custom-made tools were created amongst the selected cage applications; (a) the paper on particulate waste distribution for Atlantic salmon and (b) the design of a GIS based tool for coastal zone management personnel with only basic knowledge of GIS.

Shellfish reviews included MCE, productions models, Acoustic Classification Systems (ACS) to classify habitat types; sub-bottom and side-scan sonar; and estimates of carrying capacity for mussel and scallop culture. One review dealt with the development of a GIS based oyster management information system.

It is worth noting that very few reviews on marine cage aquaculture or shellfish included socio-economic data or field verification in their analysis. There was only one paper found in the literature on seaweeds, however, it is a good example as it illustrates how simple models can be constructed to integrate environmental and social data for decision-making.

In terms of software, most GIS applications in the present document relied on: ArcView, Idrisi and MapInfo and on the decision support tools that these three software provide.

In the context of MCE, applications show that some advances have been made on the assignments of weights and how these are combined in MCE via ranking techniques. However, since weight assignment and combination are the core of the decision making process, we believe that there is a need to further develop these weighting techniques.

TABLE 6.2
GIS-based decision-support tools for MPAs

Author	Title	Software	Aquaculture issues that could be addressed
NOAA Coastal Services Center. http://www.csc.noaa.gov/communities/agreement.html	Channel Islands - Spatial Support and Analysis Tool	CI-SSAT	Suitability of the site and zoning
University of British Columbia's Fishery Centre http://www.ecopath.org	Ecopath with Ecosim, Ecopath.	EwE	Anticipating the consequences of aquaculture
NOAA Coastal Services Center. http://www.csc.noaa.gov/mpa/stellwagen.pdf	Evaluating Vessel Speed Restrictions to Mitigate Impacts to Marine Mammals in the Stellwagen Bank National Marine Sanctuary.	ArcGIS8x tool	Anticipating the consequences of aquaculture
National Center for Caribbean Coral Reef Research.	Geographic Information and Decision Support Tool	GiDSS	Web-Based Aquaculture Information System
NOAA's Biogeography Program, National Centers for Coastal Ocean Science. http://biogeo.nos.noaa.gov/products/apps/hsm/	Habitat Suitability Modelling	HSM (HSM was designed to be used on a Windows NT computer with ArcView3.2 and requires the Spatial Analyst extension).	Anticipating the consequences of aquaculture
Rikk Kvitek, Pat Iampietro, and Erica Summers-Morris. http://seafloor.csumb.edu/publications/Kvitek_NA17OC2586_Rpt.pdf	NOAA Technical Report: Integrated Spatial Data Model Tools for Auto-Classification and Delineation of Species-Specific Habitat Maps from High-Resolution, Digital Hydrographic Data.	Methods can be performed with any GIS software that has vector and GRID/raster analysis tools.	Restoration of Aquaculture Habitats
EcoTrust http://www.ecotrust.org/gis/ocean.html	Ocean Communities 3E Analysis Network, EcoTrust.	OCEAN	Planning for aquaculture among other uses of land and water
USGS, Alaska Biological Science Center http://www.absc.usgs.gov/glba/gistools/index.htm#OCEANOGRAPHIC	The Oceanographic Analyst Extension	ArcView 3x extension and Spatial Analyst.	Suitability of the site and zoning
The Nature Conservancy. http://www.biogeog.ucsb.edu/projects/tnc/overview.html	Sites	Sites (ArcView 3x extension).	Suitability of the site and zoning
Two processes using decision support tools			
Great Barrier Reef Marine Park Authority	Great Barrier Reef Marine Park's Representative Areas Program (RAP)	MARXAN (Basic extensions of a FORTRAN 77 program SIMAN)	Suitability of the site and zoning
California Department of Fish and Game (CDFG)	EcoTrust's Use of OceanMap	Collection of scripts within an ArcView project file.	Strategic planning for development

Author	Title	Software	Aquaculture issues that could be addressed
Annotated bibliography			
Adams, Christiaan Scott. MIT, Department of Civil and Environmental Engineering. http://dogfish.mit.edu/eSite/thesis/AdamsCS_Text.pdf	An interactive, online geographic information system (GIS) for stakeholder participation in environmental site selection.	e-Site	Web-Based Aquaculture Information System
Ardron, Jeff. http://www.livingoceans.org/files/complexity_draft8.pdf	A GIS recipe for determining benthic complexity: An indicator of species richness.	A methodology is proposed.	Restoration of Aquaculture Habitats
Ardron, J., J. Lash, and D. Haggarty. Living Oceans Society. British Columbia, Canada. http://www.livingoceans.org/documents/LOS_MPA_model_v31_web.pdf	Modelling a network of marine protected areas for the central coast of British Columbia.	MARXAN (v.1.2)	Suitability of the site and zoning
Beck, M.W., M.Odaya, J.J. Bachant, J. Bergan, B. Keller, R. Martin, R. Matthews, C. Porter, and G. Ramseur. http://www.epa.gov/gmpo/habitat/NGoM_Final_allfigs.PDF	Identification of priority sites for conservation in the northern Gulf of Mexico: An ecoregional plan. The Nature Conservancy, Arlington, VA.	Sites v1.0	Suitability of the site and zoning
Grober-Dunsmor, Rikki, Jason Hale, Jim Beets, Tom Frazer, Nick Funicelli, and Paul Zwick. http://cars.er.usgs.gov/posters/Coral_and_Marine/Mngmt_of_Marine_Reserves/mngmt_of_marine_reserves.html	Applying landscape ecology principles to the design and management of marine reserves.	Not specified	Restoration of Aquaculture Habitats
Leslie, H., M. Ruckelshaus, I.R. Ball, S. Andelman,and H.P. Possingham. http://www.sam.sdu.dk/fame/menu/pdfnov/leslie.pdf	Using siting algorithms in the design of marine reserve networks. Ecological Applications.	Simulated annealing	Suitability of the site and zoning
O'Donnell, V., Cronin, M. & Cummins, V.Coastal & Marine Resources Centre, Environmental Research Institute, University College Cork, Ireland. http://www.gisig.it/coastgis/papers/o%27donnell.pdf	Sustainable coastal habitats: GIS tools for effective decision support.	Evetully a GIS, via the Internet or an ArcView extension	Environmental impacts of aquaculture
Sala, E., O. Aburto-Oropeza, G. Paredes, I. Parra, J. C.Barrera, and P. K. Dayton. http://www.cciforum.org/pdfs/Sala_Marine_Reserves.pdf	A general model for designing networks of marine reserves.	Not specified	Strategic planning for development
Sutherland, Michael, Sam Machari Ng'ang'a, and Sue Nichols. http://www.isprs.org/commission4/proceedings/pdfpapers/272.pdf	In search of New Brunswick's marine administrative boundaries.	CARIS GIS and CARIS LOTS	Suitability of the site and zoning

7. Summary, discussion and conclusions

7.1 SUMMARY

The purpose of this review is to bring to light applications of GIS, remote sensing and mapping for the development and management of marine aquaculture as a means to improve sustainability with the focus on developing countries.

Marine aquaculture

Marine aquaculture is becoming increasingly important in the fisheries sector both in production and value. Mariculture is the second most important source of production in the fisheries sector and accounted for nearly 20% of total production in the sector in 2004.

Considered by production weight in broad groups in 2004, mariculture production was dominated by aquatic plants (46%) and mollusks (43%) while diadromous fishes (salmonids) accounted for 5% and marine fishes for 4%, respectively. Crustaceans made up the remaining 2%.

Of 186 coastal countries, only 86 had a mariculture output in 2004. Of those, 15 countries accounted for 97% of the world output. Thus, there appear to be ample opportunities for the expansion of marine aquaculture among those countries not yet producing, or producing relatively little at present.

Countries have jurisdiction over development and management of all kinds within their Exclusive Economic Zones and most countries possess vast EEZ areas associated with their homelands or territories. Thus, the lack of space does not appear to be an impediment to the expansion of marine aquaculture at present.

Marine aquaculture can be viewed as occupying two environments, near shore and offshore or, the open ocean. The development of near shore aquaculture appears to be impeded by a number of issues relating to competing uses and the environment. Offshore aquaculture shares the same issues in kind, but to a lesser degree and is presently impeded by lack of open ocean technologies and an enabling framework for development.

Geographic Information Systems, remote sensing and mapping in the marine environment and fisheries sector

GIS, remote sensing and mapping aimed at aquaculture use the data and techniques applied for other purposes such as for coastal area management and fisheries, thereby making technical innovations and applications in these fields of fundamental interest. The literature on the use of these tools in the marine environment is basically promotional in nature and covers the conceptual, technical and institutional issues as well as a variety of applications. Useful stepping stones are syntheses of experience in the form of reviews and manuals. The breadth of experience is most handily available in the form of proceedings of symposia, workshops and at Internet sites.

Nevertheless, in quantitative terms GIS, remote sensing and mapping applications in aquaculture have been found to be skewed in terms of environments, species cultured, issues addressed, and countries represented. Thus, a key need was for comprehensive information on GIS, remote sensing and mapping tools as applied to aquaculture that could be widely and cheaply disseminated. GISFish, an FAO Internet portal of GIS, remote sensing and mapping experience, was created to address this problem.

Using selected examples from the literature we have shown that GIS, remote sensing and mapping have important roles to play in many geographic and spatial aspects of the development and management of marine aquaculture.

Mapping applications in marine aquaculture

Mapping is the most straightforward way to visualize spatial relationships involved with the development and management of aquaculture and one of the easiest ways to communicate the two-dimensional needs of aquaculture for space among technical people and to the public in general.

Mapping applications are shown relating to aquaculture siting and zoning, as key components of an Internet-based aquaculture information system aimed at a broad audience of government, commercial and private users, and in the form of interactive and downloadable GIS map data useful for aquaculture that are available from Internet Map Servers (IMS).

Remote sensing applications in marine aquaculture

Remote sensing, using satellite, airborne, ground and undersea sensors, is viewed mainly as a frequently and widely used tool for the capture of data subsequently to be incorporated into a marine aquaculture GIS. In this regard, hydroacoustical remote sensing is presented in the section on GIS applications to shellfish aquaculture rather than as a stand alone application. Similarly, satellite remote sensing as a source of physical data on the ocean is handled under the chapter on data. This view is not intended to diminish the importance of remote sensing relative to the other tools. On the contrary, "dynamic" remote sensing for real time, or near real time, monitoring of environmental conditions for operational management of aquaculture facilities will become increasingly important. Early warning of harmful algal blooms is one important application of this type that is covered in several examples. Dynamic remote sensing also is useful for routine monitoring of sea state, temperature, and current velocity for open ocean aquaculture.

From the early days of development to the present, digital data from satellite sensors have been useful as base maps for near shore aquaculture as well as for providing essential information on land use, land cover and some water features. Likewise, monitoring and mapping aquaculture development is another use of satellite data in areas where aquaculture is regulated.

Geographic Information Systems applications in marine aquaculture

GIS applications to near shore and offshore marine aquaculture naturally fall into two main categories: culture of finfishes in cages and near shore culture of shellfishes.

Geographic Information Systems and cage culture of finfish

Regarding cage culture, site selection and "pre-zoning" are the most numerous and most highly developed of the applications. Most of the examples pertain to pre-siting studies that cover relatively large areas, the results of which are indicative of locations with potential for further detailed field investigations among the specific areas or sites identified in the GIS. The more detailed or finer resolution data can then be incorporated in the existing GIS so that it can be used for the selection of individual sites.

There is a clear evolution from site selection in which only the suitability for the culture system and cultured organisms are taken into account to broader-based studies in which the objective is to accommodate marine aquaculture amongst competing uses. Going along with this is increasing sophistication in decision-making that includes the use of experts and formalized procedures to identify and quantify production functions in models. The result is more complete and reliable information on which to base decisions.

More specialized investigations of cage culture use GIS to address wave climate and cage effluents.

Geographic Information Systems and shellfish culture

GIS applications to shellfish culture are much more numerous than for cage culture of fish for a number of reasons relating to the much greater production of the former. On issues related to development, the reviews cover applications on siting, estimating potential, anticipating competing uses and avoiding conflicts. Regarding issues relating to aquaculture practice and management, the reviews address, pollution, diseases in aquaculture operations, habitat evaluation using hydroacoustical remote sensing, resources, carrying capacity, and seasonal mortality.

Most of the applications are aimed at oysters, but hard clams, mussels and scallops are included. Most of the culture takes place on the bottom although raft and longlines are represented.

Among the problems that continue to impede these applications is a lack of data of sufficient scope or resolution. This may be related to a paucity of studies in which decision-making is formalized in an objective way.

Among the gaps are applications that identify shore support facilities along with sites or zones for culture. Surrogates for such applications are site selection studies for shrimp farming in ponds that have many data layers in common.

Economics and Geographic Information Systems

Given that all spatial aspects of marine aquaculture have an economic underpinning, it is noteworthy that there is a dearth of GIS applications to the economic aspects of marine aquaculture development and management. This is despite the fact that some existing economic studies and models clearly lay out geographically related cost variables. It has been suggested that GIS could be applied to several elements of these economic studies to improve choices of tradeoffs mainly by spatially hindcasting environmental variables.

The few applications of GIS in socio-economics are mainly global studies that encompass all of aquaculture. The potential of GIS to contribute to the improvement of human welfare in the development of marine aquaculture at sub-national levels is beginning to be realized.

Data availability

Data of the appropriate temporal and spatial resolution as well as geographic coverage for the intended use is one of the most important considerations for GIS implementation. Early investigators were well aware of the spatial factors and constraints associated with marine aquaculture. Their main difficulty was in finding or generating data appropriate to the task. To some extent this problem continues today and is manifest in the lack of some kinds of compiled data, among which currents stand out. Spatial gaps in data, and data of too low resolution continue to be issues.

There usually is a fairly close correlation between data resolution and geographic coverage. Thus, for marine aquaculture spatial investigations, data sets can be conveniently categorized as global, national, sub-national and local in consideration of the spatial area of interest. Temporal characteristics of the data sets also are important. For "static" data such as shorelines access to the most recent updates is necessary. For dynamic data such as SST, temporal needs may range from climatologies based on years of observations to real time data, the latter for operational management of aquaculture installations and the former for commercial or governmental development planning.

Attribute data are used to set thresholds on production factors. Attribute data may take a long time to identify, compile and synthesize because of the need for extensive literature and Internet searches as well as for correspondence with experts.

With the objective of pointing the way to data that could be used for a first approximation of offshore aquaculture potential, we have placed our emphasis on describing data that have a global coverage and that are mainly freely downloadable from the Internet. The most basic of these data sets include shorelines, EEZ boundaries, bathymetry, SST, and chlorophyll-a.

Real time data, and more importantly predictions that can be made based on them, can be vital for the operational management of marine aquaculture installations. We point the way to sources of real time data that include SST, chlorophyll, wave heights and current velocity.

Data sets at national and sub-national resolutions appear to vary greatly in availability among countries. Obviously, there is a correlation between the availability of data and the numbers of applications in marine aquaculture. The current count on applications by country at GISFish casts light on this problem.

Models and decision-making in marine aquaculture

Our impression is that there is a need to go further beyond the fisheries sector in order to pick up the latest methods and applications for GIS-based decision support. It is our belief that many lessons can be learnt from MCE used in other sectors such as MPAs analysis (Pattison, dos Reis and Hamilton, 2004), integrated coastal management decision support frameworks (e.g. Fabbri, 2006) and location-based methodologies applied by the business community. It was not possible to conduct a detailed review of MCE for marine aquaculture, but we may conclude that a separate paper on the state of Decision Support Tools (DST) in the aquaculture sector would be a much needed contribution and it could be used as a guideline for future work on MCE for the development and management of marine aquaculture. To this end, Leung (2006) provides an up-to-date review of MCE applications in fishery management. Therefore, a review on MCE for aquaculture is considered complementary and very timely.

7.2 DISCUSSION AND CONCLUSIONS

Marine aquaculture

- Marine aquaculture overall is growing rapidly and offshore aquaculture is becoming more important as more experience is gained. From a spatial point of view there appear to be ample opportunities for the expansion of offshore marine aquaculture in countries presently producing little or not producing at all in this sector.
- Sustainable growth of marine aquaculture will require an enabling environment that includes sound plans for continued development and management. Such plans can come only by addressing and successfully resolving the main issues concerned. According to Muir (2004), the main questions in open ocean aquaculture are:
    - Can complete offshore systems be defined and developed?
    - Can these be developed and operated in a cost-effective manner?
    - What are the economic implications?

  - Will they be suitable for regional conditions?
  - Will there be an appropriate policy environment?
  - Will there be the appropriate market and investment conditions to stimulate their use?
- Along these lines, it has been emphasized by Cicin-Sain *et al*. (2005) that the development and operation of an offshore farm requires an investment running to millions of dollars and they note that siting decisions based on insufficient or faulty information can create costly delays, environmental degradation, conflicts with other users, reduced production, leasing issues, licensing and other regulatory requirements, or ultimately, project failure.

GIS, remote sensing and mapping applications

- GIS, remote sensing and mapping applications have been assembled to illustrate the capabilities of these tools to address many issues facing the development and management of marine aquaculture. We have framed the applications in a broad set of fundamental aquaculture issues. Obviously, the emphasis on some issues may vary from situation to situation, and new issues may arise. In any case, we deem it essential that the deployment of spatial tools is based on a careful prior assessment of issues. Although there is much room for refinement as well as for the expansion of applications to more fully and broadly address issues, it is safe to say that these tools can be advantageously deployed to improve the sustainability of marine aquaculture, particularly for pre-siting and identifying and quantifying competing and conflicting uses. Said differently, the use of GIS, remote sensing and mapping has reached the point of becoming an essential part of providing the enabling environment for the development of marine aquaculture.
- A noteworthy gap is that the culture of marine plants, by weight the most important output of marine aquaculture, has not been fully covered by GIS, only one application was found in the literature.
- A legitimate question is that, despite the many varieties of applications presented herein, why is the use of GIS, remote sensing and mapping in aquaculture not more common and widespread as in other disciplines such as water resources? We believe that part of the answer is a lack of information about the capabilities of these tools among administrators and managers and a lack of access to experience among practitioners, especially in developing countries. This technical paper represents one solution and GISFish is another. However, other possible constraints need to be considered. One is that there is too little opportunity for formal education in GIS that should accompany undergraduate and graduate studies in all fields of natural resource research and management. Another is lack of access to computer equipment, software and the bandwidth in order to operate on the Internet effectively, especially with regard to communicating and acquiring data and especially in developing countries. Clearly, the impediments to more effective and widespread use of spatial tools in aquaculture need to be examined. Possibilities for next steps in this direction include the formation of a FAO-sponsored working group to address specific items that could include (1) a review of the aquaculture sector's present and future needs for spatial analyses, (2) a critical analysis of why GIS has not taken off, and (3) the role GIS, remote sensing and mapping for the management and development of aquaculture and in strategic and operational decision-making. The discussion forum offered by GISFish could be the initial meeting place for the working group. As a means of broadening the input to the working group, it could meet in conjunction with an international meeting such as the International Symposium on GIS and Spatial Analysis in Fishery

and Aquatic Sciences. Another way to broaden the perspective of the working group would be to empanel members from disciplines other than fisheries and aquaculture in which the use of GIS has become widespread and effective (e.g., coastal area management). A report as the final output of the working group would not be sufficient. Rather, the working group should be convened not just with the idea of identifying problems, but also with the mandate to design practical solutions, and to identify organizations with the capabilities to finance and implement the solutions.

Economics, socio-economics and GIS

- There is a dearth of applications of GIS to the economic issues of aquaculture. It is ironic that, in contrast to many other kinds of applications, the economic data appear to be readily available for GIS analysis from economic studies in which spatial analysis has not been employed. Some examples are highlighted below.
- Spatial bioeconomic modelling requires estimating spatial differences in culture production. A step in coupling GIS with bioeconomic modelling was taken by Kapetsky and Nath (1997) who integrated a GIS with a bio-energetics model to assess inland aquaculture potential in Latin America, and Aguilar-Manjarrez and Nath (1998) followed a similar procedure for Africa.
- It appears that there are many other opportunities for integrating GIS with already-developed marine aquaculture bioeconomic models. For example, Kite-Powell *et al*. (2003) have developed a bioeconomic model for open-ocean finfish culture in the Atlantic off of the New England region of the United States of America that they have applied to salmon, cod and flounder. The model optimizes stocking and harvesting schedules, projects financial flows and allows for alternative grow-out sites. Among the spatial (locational) parameters that figure in their model is water temperature related to growth, depth related to mooring and installation costs of cages, wave profile, and distance from shore. Because their model calculates the financial performance of the operation month by month over a 15-year period, there is an unrealized opportunity to make the model more dynamic temporally and spatially by hind casting performance in a GIS by employing monthly historical SST and/or Drifter data. The authors deemed distance traveled and vessel operating and crew expenses as substantial costs to the overall operation. In this regard they conclude that it makes good economic sense to locate grow-out sites as close to shore as possible, given other constraints. GIS could be applied to this problem as well, not only in locating the sites that would be most suitable distance-wise, but also by estimating the risk in terms of variability by hind casting sea and weather conditions affecting boat operating and performance in a way similar to spatial variability in growth performance as outlined above.
- GIS could be applied in similar ways to the economics of shellfish culture, but there are differing needs for analyses. Langan and Forbes (2003), describe the design, operation and economics of submerged longline mussel culture in the open ocean. They indicate that food quality and quantity are the most important factors affecting grow-out time. Thus, identifying areas with consistently high chlorophyll-a, low turbidity and relatively high dissolved oxygen would be important considerations in consideration of limiting boat travel time. Kite-Powell, Hoagland and Jin (2003) studied the economics of open ocean grow-out of sea scallops (*Plagopecten magellanicus*) and blue mussels. Grow-out of the former species would depend on reliable capture fisheries for juveniles, thus adding a criterion for site selection that would be

areas with suitable sea scallop juvenile stocks and with available fishing craft and personnel to supply the culture operation. Hoagland, Kite-Powell and Lin (2003) developed a business plan for open ocean culture of mussels in the New England, the United States of America area. They estimate vessel operation costs, including crew, at $1,000/d for 90 days/y at sea. Once the operation is well established, these costs account for from 21% to 23% of the total cost of the operation. Therefore, site selection that minimizes vessel "commuting" time, along with the other needs outlined above, is quite important for the business plan and the sustainability of the operation.

Estimating open ocean aquaculture potential

- The study of open ocean aquaculture potential in the US EEZ (Section 4) clearly illustrates that it is possible to create a simple GIS to make a first approximation of offshore aquaculture potential for any country wishing to do so. The basis for such studies is sufficient spatial data with global coverage that are freely available for download from the Internet. Attribute data have to be identified, compiled and synthesized according to the culture systems and species appropriate to the country's marine waters.

Data availability

- There are two data problems that impede the use of GIS in marine aquaculture, one of which is access to spatial data and the other of which is the availability of attribute data. Regarding spatial data, there are still many data gaps that fall into three categories: (1) gaps in geographic coverage and time, (2) resolution, and (3) gaps in kinds of data. Most of the time spent in a GIS study of marine aquaculture can go to identifying, collecting, organizing and compiling the attribute data that define the environmental requirements for the culture of organisms and for the optimum and working limits for culture structures.

Data models and decision-making in marine aquaculture

- Key improvements on decision support tools (DST) for marine aquaculture include: an increased use of socio-economic data, and the development of custom made tools and/or the use of DST used/created in other sectors to better address specific decision problems for marine aquaculture. Given the contrasts between the DST tools used in the GIS applications described in the present document and those used in MPA analysis it is believed that better communication amongst experts from different sectors would enhance DST for marine aquaculture. Also, the impression is that more marine aquaculture experts with more experience on MCE are required to fully benefit from existing tools and/or to create new tools.

Final consideration and recommendations

- The potential of spatial tools can be realized through cooperative, cross-disciplinary approaches that emphasize addressing common issues and by constituting teams with expertise on each of the ramifications of the issues.
- From the viewpoint of organization and implementation of GIS, it is clear that marine fisheries and marine aquaculture share common needs for environmental and economic data, and many of the species are both cultured and captured. Furthermore, spatial analytical procedures are the same or similar in marine aquaculture and fisheries. Therefore, it would seem that there is much to be gained by cooperation between, or integration, of GIS activities in aquaculture and fisheries at national government levels and among academic institutions.

- From the viewpoint of attribute data for thresholding, there is a need for (1) syntheses of information on the biophysical requirements of species presently being cultured, or with potential for marine aquaculture, (2) physical environmental requirements of culture structures, and (3) bioeconomic models.

8. Glossary

Geographic Information Systems A computer system for capturing, storing, checking, integrating, manipulating, analysing and displaying data related to positions on the Earth's surface. Typically, a Geographical Information System (or Spatial Information System) is used for handling maps of one kind or another. These might be represented as several different layers where each layer holds data about a particular kind of feature. Each feature is linked to a position on the graphical image of a map. In aquaculture, it has been used to assess the suitability of geographical sectors, and also to investigate the suitability of a species to an area.

ENVISAT (Environment Satellite). ENVISAT satellite is an Earth-observing satellite built by the European Space Agency. It was launched on March 1, 2002 aboard an Ariane 5 into a Sun synchronous polar orbit at a height of 790 km (+/– 10 km). It orbits the Earth in about 101 minutes with a repeat cycle of 35 days

Fuzzy classification Any method for classifying data that allows attributes to apply to objects by membership values, so that an object may be considered a partial member of a class. Class membership is usually defined on a continuous scale from zero to one, where zero is nonmembership and one is full membership. Fuzzy classification may also be applied to geographic objects themselves, so that an object's boundary is treated as a gradated area rather than an exact line. In GIS, fuzzy classification has been used in the analysis of soil, vegetation, and other phenomena that tend to change gradually in their physical composition and for which attributes are often partly qualitative in nature.

Geodatabase A collection of geographic datasets for use by ArcGIS. There are various types of geographic datasets, including feature classes, attribute tables, raster datasets, network datasets, topologies, and many others.

Keyhole Markup Language XML grammar and file format for modelling and storing geographic features such as points, lines, images, polygons, and models for display in Google Earth. A KML file is processed by Google Earth in a similar way that HTML and XML files are processed by web browsers. Like HTML, KML has a tag-based structure with names and attributes used for specific display purposes. Thus, Google Earth acts as a browser of KML files.

Landsat The U.S. Landsat satellites are the first series of Earth Observation satellites providing global, repeated coverage of the Earth surface. The sensors onboard these satellites operate in the visible up to middle infrared wavelengths, and in the thermal infrared. The first satellite of the mission, ERTS-1 (later renamed Landsat-1) was launched in 1972. The current Landsat-7 mission hosts the Enhanced Thematic Mapper sensor; of its nine channels, seven acquire data in the visible up to middle infrared, at 30 m resolution. More information on the Landsat-7 mission can be found in the USGS Web pages (http://landsat7.usgs.gov/index.php) and in the NASA Web pages (http://landsat.gsfc.nasa.gov/).

Maps Graphic representation of the physical features (natural, artificial, or both) of a part or the whole of the Earth's surface, by means of signs and symbols or photographic imagery, at an established scale, on a specified projection, and with the means of orientation indicated.

Marine aquaculture Cultivation, management and harvesting of marine organisms in their natural habitat or in specially constructed rearing units, e.g. ponds, cages, pens, enclosures or tanks. For the purpose of FAO statistics, mariculture refers to cultivation of the end product in seawater even though earlier stages in the life cycle of the concerned aquatic organisms may be cultured in brackish water or freshwater.

MCE is a decision support tool for Multi-Criteria Evaluation. A decision is a choice between alternatives (such as alternative actions, land allocations, etc.). The basis for a decision is known as a criterion. In a Multi-Criteria Evaluation, an attempt is made to combine a set of criteria to achieve a single composite basis for a decision according to a specific objective. For example, a decision may need to be made about what areas are the most suitable for industrial development. Criteria might include proximity to roads, slope gradient, exclusion of reserved lands, and so on. Through a Multi-Criteria Evaluation, these criteria images representing suitability may be combined to form a single suitability map from which the final choice will be made.

MERIS (Medium Resolution Imaging Spectrometer). MERIS is a programmable, medium-spectral resolution, imaging spectrometer operating in the solar reflective spectral range. Fifteen spectral bands can be selected by ground command, each of which has a programmable width and a programmable location in the 390 nm to 1 040 nm spectral range. The instrument scans the Earth's surface by the so called "push-broom" method. Linear CCD arrays provide spatial sampling in the across-track direction, while the satellite's motion provides scanning in the along-track direction. MERIS is designed so that it can acquire data over the Earth whenever illumination conditions are suitable. The instrument's 68.5° field of view around nadir covers a swath width of 1150 km. This wide field of view is shared between five identical optical modules arranged in a fan shape configuration.

Metadata Information that describes the content, quality, condition, origin, and other characteristics of data or other pieces of information. Metadata for spatial data may describe and document its subject matter; how, when, where, and by whom the data was collected; availability and distribution information; its projection, scale, resolution, and accuracy; and its reliability with regard to some standard. Metadata consists of properties and documentation. Properties are derived from the data source (for example, the coordinate system and projection of the data), while documentation is entered by a person (for example, keywords used to describe the data).

Pixels (Picture elements) Cells of an image matrix. The ground surface corresponding to the pixel is determined by the instantaneous field of view (IFOV) of the sensor system, e.g. the solid angle extending from a detector to the area on the ground it measures at any instant. The digital values of the pixels are the measures of the radiant flux of electromagnetic energy emitted or reflected by the imaged Earth surface in each sensor channel.

Projection A method by which the curved surface of the earth is portrayed on a flat surface. This generally requires a systematic mathematical transformation of the earth's graticule of lines of longitude and latitude onto a plane. Some projections can be visualized as a transparent globe with a light bulb at its center (though not all projections emanate from the globe's center) casting lines of latitude and longitude onto a sheet of paper. Generally, the paper is either flat and placed tangent to the globe (a planar or azimuthal projection) or formed into a cone or cylinder and placed over the globe (cylindrical and conical projections). Every map projection distorts distance, area, shape, direction, or some combination thereof.

Remote Sensing The gathering and analysis of data from the study area or organism that is physically removed from the sensing equipment, e.g. sub-water surface detection instruments, aircraft or satellite.

SAR (Synthetic Aperture Radar) An imaging radar is an active instrument that transmits microwave pulses toward the Earth surface and measures the magnitude of the signal scattered back towards it. The return signals from different portions of the ground surface are combined to form an image. A Synthetic Aperture Radar (SAR) is a special type of imaging radar. It is a complex system that measures both the amplitude and phase of the return signals; their analysis exploits the Doppler effect created by the motion of the spacecraft with respect to the imaged surface to achieve high ground resolution. As the source of the electromagnetic radiation used to sense the Earth surface is the system itself, it can be operated during day and night. The atmospheric transmittance in the microwave interval used by remote sensing SAR systems (2 to 30 GHz) is higher than 90%, also in presence of ice and rain droplets (except under heavy tropical thunderstorms); thus, SAR can acquire data in all weather conditions.

Scale The ratio between a distance or area on a map and the corresponding distance or area on the ground.

Resolution The area of the ground surface corresponding to a pixel in a satellite image.

Glossary compiled from the following sources:

Anonymous. 1998. AQUALEX. Multilingual glossary of aquaculture terms/ Glossaire multilingue relatif aux termes utilisés en aquaculture. CD ROM, John Wiley & Sons Ltd. & Praxis Publ., UK.

Association for Geographic Information (AGI) GIS Dictionary (http://www.geo.ed.ac.uk/agidict/welcome.html)

Barnabé, G. (ed..) 1990 Aquaculture. Chichester, UK, Ellis Horwood. Vol.1, 528p. Vol.2, 584p. Transl. by L.M. Laird.

Center for Spatially Integrated Social Science (CSISS): http://www.csiss.org/cookbook/glossary.php

Choudury, K. and Jansen, L.J.M. (UNESCO/WMO) 1999. Terminology for integrated resources planning and management. Rome, FAO. 69p.

Chrisman, N. Glossary for Exploring GIS, by: http://www.wiley.com/college/chrisman/glossary.html

Earth Sciences Sector of Natural Resources Canada. Canada Center for Remote Sensing (CCRS). Glossary of remote sensing terms (http://ccrs.nrcan.gc.ca/glossary/index_e.php).

ESRI. 2001. *The ESRI Press dictionary of GIS terminology*. Environmental Systems Research Institute, Inc. Redlands, California, USA (available at: http://www.esri.com/library/glossary/a_d.html).

FAO 2006.Glossary of Aquaculture. http://www.fao.org/fi/glossary/aquaculture/

FAO Fisheries Department 2003 World Fisheries and Aquaculture Atlas. CD-ROM. Rome, FAO. 2nd ed.

Hoehn, P., and Lynette, M. Dictionary of abbreviations and acronyms in geographic information systems, cartography and remote sensing. (available at http://www.lib.berkeley.edu/EART/abbrev.html).

Perry-Castañeda Library Map Collection. Glossary of Cartographic Terms online at http://www.lib.utexas.edu/maps/glossary.html. The University of Texas.

Voser, S.A. Glossary of glossaries (available at http://www.geocities.com/CapeCanaveral/1224/terms/terms_txt.html)

References

Aguilar-Manjarrez, J. 1992. Construction of a GIS for Tabasco State Mexico. Establishment of technical and social decision models for aquaculture development. Institute of Aquaculture.University of Stirling, UK. 125 pp. (M.Sc.Thesis).

Aguilar-Manjarrez, J. 1996. Development and evaluation of GIS-based models for planning and management of coastal aquaculture: a case study in Sinaloa, México. Institute of Aquaculture, University of Stirling, Scotland, UK. 373 pp. (Ph.D. Thesis).

Aguilar-Manjarrez, J. & Nath, S.S. 1998. *A strategic reassessment of fish farming potential in Africa.* CIFA Technical Paper. No. 32. FAO, Rome. 170 pp. (also available at http://www.fao.org/docrep/W8522e/W8522E00.htm).

AquaGIS. 2006. Newfoundland and Labrador Aquaculture Geographic Information System. Department of Fisheries and Aquaculture, Newfoundland and Labrador. (available at www.aquagis.com).

Arnold, W.S., Norris, H.A. & Berrigan, M.E. 1996. Lease site considerations for hard clam aquaculture in Florida. *Journal of Shellfish Research* 15:478-479.

Arnold, W.S. & Norris, H.A. 1998. Integrated resource management using GIS: Shellfish aquaculture in Florida. *Journal of Shellfish Research* 17: 318.

Arnold, W.S., Kaiser, J.B. & Holt, G.J. 2002. Spawning of Cobia (*Rachycentron canadum*) in captivity. *Journal of the World Aquaculture Society*, 33(2): 205-208.

Arnold, W.S., White, M.W., Norris, H.A. & Berrigan, M.E. 2000. Hard clam (*Mercenaria spp.*) aquaculture in Florida, USA: geographic information system applications to lease site selection. *Aquacultural Engineering*. 23(1-3):203-231.

Auckland Regional Council. 2002. Mapping constraints to future marine farming in the Auckland and Waikato Regions-Stage One. 96 pp.

Auckland Regional Council (no year). Mapping Potential Aquaculture Management Areas in the Auckland Region – Stage 2. (available at http://www.arc.govt.nz/arc/library/b86166_2.pdf).

Bacher, C., Grant, J., Hawkins, A.S.J., Fang, J., Zhu, M. & Besnard, M. 2003. Modelling the effect of food depletion on scallop growth in Sungo Bay (China). *Aquatic Living Resources*, 16(1): 10-24.

Basurco, B. & Sarologia, M. 2002. Seafarming today and tomorrow. European Aquaculture Society. Special Publication No. 32. 562 pp.

Belton, V. & Stewart, T.J. 2002. Multi Criteria Decision Analysis and Integrative Approaches, Kluwer Academic Publishers, New York.

Beveridge, M. 2004. *Cage Aquaculture*. Third Edition. Blackwell Publishing. London. 376 pp.

Booth, A.J. 2004. Spatial statistics and aquatic Geographic Information Systems. In Nishida, T., Kailola, P. and Holliingworth, C. eds. GIS/Spatial analyses in fishery and aquatic sciences (Vol 2.) Proceedings of the Second International Symposium on GIS/Spatial analyses in fishery and aquatic sciences. pp. 3-44. Fishery-Aquatic GIS Research Group. Kawagoe, Saitama, Japan. 733 pp.

Booth, A.J. & Wood, B. 2004. Geographic Information Systems application in offshore marine fisheries. *In* Fisher, W. L. and Rahel, F.J. eds. Geographic information systems in fisheries. pp. 209-236. American Fisheries Society, Bethesda, Maryland, USA. 275 pp.

Breman, J. ed. 2002. Marine geography. GIS for the oceans and seas. ESRI Press. Redlands, California, USA. 204 pp.

Bremen, J., Wright, D. & Halpin, P.N. 2002. The inception of the ArcGIS marine data model. In Breman, J. ed. Marine geography. GIS for the oceans and seas. Pp 3-10. ESRI Press. Redlands, California, USA. 204 pp.

Bridger, C.J. & Costa-Pierce, B.A. eds. 2003. Open Ocean Aquaculture: From Research to Commercial Reality. The World Aquaculture Society, Baton Rouge, Louisiana, USA. 351 pp.

Bridger, C.J., Costa-Pierce, B.A., Goudey, C.A., Stickney, R.R. & Allen, J.D. 2003. Offshore aquaculture development in the Gulf of Mexico: Site selection, candidate species, and logistic alleviation. In Pages 273–283 C.J. Bridger and Costa-Pierce, B.A., eds. Open Ocean Aquaculture: From Research to Commercial Reality. The World Aquaculture Society, Baton Rouge, LA.

Buitrago, J., Rada, M., Hernández, H. & Buitrago, E. 2005. A Single-Use Site Selection Technique, Using GIS, for Aquaculture Planning: Choosing Locations for Mangrove Oyster Raft Culture in Margarita Island, Venezuela. Environmental Management 35(5): 544-556.

Burrough, P.A. 1986. Principles of Geographic Information Systems, 1st ed. Oxford University Press, New York 336 pp.

Butler, M.J.A, LeBlanc, C., Belbin, J.A. & MacNeill, J.L. 1987. *Marine resource mapping : an introductory manual.* FAO Fisheries Technical Paper No. 274. Rome, FAO. 256 pp.

Butler, M.J.A., Mouchot, M.-C., Barale, V. & LeBlanc, C. 1988. *The application of remote sensing technology to marine fisheries : an introductory manual.* FAO Fisheries Technical Paper No. 295. Rome, FAO.

Carswell, B., Cheesman, S. & Anderson, J. 2006. The use of spatial analysis for environmental assessment of shellfish aquaculture in Baynes Sound, Vancouver Island, British Columbia, Canada. Aquaculture, 253(1-4): 408-414.

Center for Coastal Resources Management. 1999. Shallow water resource use conflicts: Clam aquaculture and submerged aquatic vegetation. Virginia Institute of Marine Science, Gloucester Point, Virginia. 30 pp.

Chang, B., Page, F.H. & Hill, W.H. 2005. Preliminary analysis of coastal marine resources use and the development of open ocean aquaculture in the Bay of Fundy. Canadian Technical Report of Fisheries and Aquatic Sciences 2585. 36 pp.

Cicin-Sain, B Knecht, R. W., Rheault, R., Bunsick, S.M., DeVoe, R., Eichenberg, T., Ewart, J. & Halvorson, H. 2001. Development of a Policy Framework for Offshore Marine Aquaculture in the 3-200 Mile U.S. Ocean Zone. Center for Marine Policy, University of Delaware. 167 pp.

Cicin-Sain, B., Bunsick, S.M., Corbin, J., DeVoe, R. M., Eichenberg, T., Ewart, J., Firestone, J., Fletcher, K., Halvorson, H., MacDonald, T., Rayburn, R., Rheault, R. & Thorne-Miller, B. 2005. Recommendations for an operational framework for offshore aquaculture in U.S. Federal waters. Center for Marine Policy, University of Delaware. 118 pp.

CINEMAR. 2005. News Release. New Hampshire Fishermen Are Mussel Bound. (available at http://ooa.unh.edu/news/1_2005/newsMussels.htm).

Cordell, E.V. & Nolte, D.A. 1998. Feasibility of using remote sensing to identify the aquaculture potential of coastal waters. Recon Technologies, Inc. Bend, Oregon, USA.

Corner, R.A., Brooker, A.J., Telfer, T.C. & Ross, L.G. 2006. A fully integrated GIS-based model of particulate waste distribution from marine fish-cage sites. Aquaculture 258: 299–311. (also available at http://www.aqua.stir.ac.uk/GISAP/pdfs/Corner_waste.pdf).

De Graaf, G., Marttin, F., Aguilar-Manjarrez, J. & Jenness, J. 2003. *Geographic information systems in fisheries management and planning. Technical manual.* FAO Fisheries Technical Paper No. 449. FAO, Rome. 162pp. (also available at http://www.fao.org/docrep/006/y4816e/y4816e00.htm#Contents).

DeMers, M.N. 2003. Fundamentals of Geographic Information Systems. Second Edition. John Wiley and Sons, Inc. New York, NY, USA. 636 pp.

Dolmer, P. & Geitner, K. 2004. Integrated Coastal Zone Management of cultures and fishery of mussels in Limfjorden, Denmark. ICES C.M. 2004/V:07. 9 pp.

Dooley J.F. 2005. An Inventory and Comparison of Globally Consistent Geospatial Databases and Libraries. *Environment and Natural Resources Series* No.19 - FAO, Rome. 200 pp. (also available at http://www.fao.org/docrep/008/a0118e/a0118e00.htm#Contents).

Durand, H., Guillaumont, B., Loarer, R., Loubersac, L., Prou, J. & Heral, M. 1994a. An example of GIS potentiality for coastal zone management: pre-selection of submerged oyster culture areas near Marennes Oléron (France). EARSEL Workshop on Remote Sensing and GIS for Coastal Zone Management. Delft, The Netherlands.

Durand, H., Guillaumont, B. & Labbe, S. 1994b. Maquette d'un SIG littoral en vue de la recherche de sites ostreicoles en eau profonde. Gutlar/IFREMER Groupe Sillage. Brest, France. (pages not numbered).

El Gayar, O.F. & Leung, P.S. 2006. A multiple-criteria decision making framework for regional aquaculture development. *European Journal of Operational Research* Vol. 133, pp 462-482.

Environment Bay of Plenty. 2006. Aquaculture Managament Area Project. (available at http://www.ebop.govt.nz/Coast/AMA-project.asp).

Fabbri, K.P. 2006. A strategic decision support framework for integrated coastal zone management. *Int. J. Environmental Technology and Management*, Vol. 6, Nos. 1/2, pp 206-217.

FAO. 1995. Code of conduct of responsible fisheries. FAO, Rome. (available at http://www.fao.org/DOCREP/005/v9878e/v9878e00.htm#PRE).

FAO. 1997. FAO Technical Guidelines for Responsible Fisheries. Aquaculture Development No. 5. Rome, FAO. 40 pp.

FAO. 2006a. FISHSTAT PLUS [online]. Universal software for fishery statistical time series [Version 2.3]. Release date: March 2006. (available at http://www.fao.org/fi/statist/FISOFT/FISHPLUS.asp).

FAO.2006b. Glossary of Aquaculture. Rome, FAO. (available at http://www.fao.org/fi/glossary/aquaculture/).

Field, D. 2001. Practical aquaculture GIS. INFOFISH International 5: 27-30.

Fisher, W.L. (in press). Recent trends in fisheries geographic information systems. In Nishida, T., Kailola, P. and Holliingworth, C. eds. Proceedings of the Third International Symposium on GIS/Spatial analyses in fishery and aquatic sciences. Fishery-Aquatic GIS Research Group. Kawagoe, Saitama, Japan.

Fisher, W.L. & Rahel, F.J. eds. (2004). Geographic information systems in fisheries. American Fisheries Society, Bethesda, Maryland, USA. 275 pp.

Freddi, A. & Aguilar-Manjarrez, J. 2005. TCP/BRA/0065. Small-scale seaweed farming in North East Brazil. FAO Aquaculture Newsletter December 2005 - No. 34. FAO, Rome, pp 34-35 (also available at http://www.fao.org/docrep/009/a0435e/a0435e00.htm).

Geitner, K. 2004. Use of GIS for placement of rainbow trout culture in Denmark. In Nishida, T., Kailola, P. and Holliingworth, C. eds. GIS/Sparial analyses in fishery and aquatic sciences (Vol 2.) Proceedings of the Second International Symposium on GIS/Spatial analyses in fishery and aquatic sciences. pp. 543-558. Fishery-Aquatic GIS Research Group. Kawagoe, Saitama, Japan. 733 pp.

GEODAS. 2006. Grid Translator. National Geophysical Data Center. NOAA Satellite and Information Service. (available at http://www.ngdc.noaa.gov/mgg/gdas/gd_designagrid.html).

GESAMP (IMO/FAO/UNESCO-IOC/WMO/WHO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Environment Protection (GESAMP). 2001. Planning and management for sustainable coastal aquaculture development. GESAMP Reports and Studies. 68. 45 pp. (also available at ftp://ftp.fao.org/docrep/fao/007/y1818e/y1818e00.pdf).

Goudey, C. 1998. Model Tests and Operational Optimization of a Self-propelled Open-ocean Fish Farm. In Biran, A. Ed. Proceedings Offshore Technologies for Aquaculture. Haifa, Israel, 13-16 Oct. 1998.

Goulletquer, P., Soletchnik, P., Le Moine, O., Razet, D., Geairon, P., Faury, N. & Taillade, S. 1998. Summer mortality of the Pacific cupped oyster *Crassostrea gigas* in the Bay of Marennes-Oleron (France). International Council for the Exploration of the Sea Copenhagen (Denmark) Theme Session on Population Biology. ICES, Copenhagen, Denmark. 20 pp.

Goulletquer, P. & Le Moine, O. 2002. Shellfish farming and Coastal Zone Management (CZM) development in the Marennes-Oléron Bay and Charentais Sounds (Charente Maritime, France): A review of recent developments. Aquaculture International, 10(6): 507-525.

Guneroglu, A., Kose ,E., Eruz, C., Basar, E., Erkebay, S. & Karsli, F. 2005. Use Of Geographic Information System (GIS) To Select Fish Cage Farming Sites In Surmene Bay, Black Sea. *The Israeli Journal of Aquaculture* – Bamidgeh 57(2), 2005, 81-89.

Handisyde, N.L., Ross, L.G, Badjeck, M.-C. & Allison, E.H. 2006. The effects of climate change on world aquaculture. A global perspective. DFID, UK. (available at http://www.aquaculture.stir.ac.uk/GISAP/pdfs/Climate_full.pdf).

Hoagland, P., Kite-Powell, H. L. & Lin, D. 2003. Business Planning Handbook For The Ocean Aquaculture Of Blue Mussels. Marine Policy Center Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA. 31 pp.

Hughes Clark, J.E., Wildish, D. & Duxfield, A. 2002. Acoustic imaging of salmonid mariculture sites. CHC 2002 Proceedings. 17 pp.

Inglis, G.J., Hayden, B.J. & Ross, A.H. 2000. An overview of factors affecting the carrying capacity of coastal embayments for mussel culture. NIWA Client Report: CHC00/69 Project No. MFE00505. National Institute of Water and Atmospheric Research Ltd Christchurch New Zealand. 31 pp.

Island Institute. 1999. The Maine Guide to Mussel Raft Culture. Island Institute, Rockland, Maine, USA. 32 pp.

Jacquet, J.-M. 1987. Remote sensing evaluation of water quality in the Gulf of Nicoya (Costa Rica). Annex 1. in Kapetsky, J.M. McGregor, L. and Nanne E., H. (1987). *A geographical information system and satellite remote sensing to plan for aquaculture development: a FAO-UNDP/GRID cooperative study in Costa Rica.* FAO Fisheries Technical Paper No. 287. Rome, FAO.

Janssen, R. & van Herwijnen, M. 2006. A toolbox for multiple criteria decision-making. *Int. J. Environmental Technology and Management*, 6 (1/2): 20-39.

Jefferson, W.H., Michener, W.K., Karinshak, D.A., Anderson, W., & Porter, D.E.1991. Developing data layers for estuarine resource management. Proceedings of GIS/LIS '91. Inforum, Atlanta, Georgia. 1: 331-342.

Johannessen, J.A., Johannessen, O.M. & Haugan, P.M. 1988. Remote sensing and model simulation studies of the Norwegian coastal current during the algal bloom in May 1988. The Nansen Remote Sensing Center. Technical Bulletin No. 16.

Jordan, S.J., Greenhawk, K.N. & Smith, G. F. 1995. Maryland oyster geographical information system: Management and scientific applications. *Journal of Shellfish Research* 14: 269.

Jordana, R. 2004. SIG–Pesca. Sistema deInformación Geográficade la Direcció General de Pesca i Afers Marítims. Lecture delivered at the CIHEAM Advanced Course on Offshore Mariculture, Zaragoza (Spain), 17-22 May 2004 (available at http://www.easonline.org/agenda/en/description.asp?id=264).

Kapetsky,J.M. 1989. A geographical information system for aquaculture development in Johor State. FAO Technical Cooperation Programme Project. Land and Water Use Planning for Aquaculture Development.TCP/MAL/6754. Field Document. FAO, Rome.

Kapetsky, J.M. 2004. Geographic information systems applications in aquaculture. In Fisher, W. L. and Rahel, F.J. eds. Geographic Information Systems in fisheries. pp. 13-48. American Fisheries Society, Bethesda, Maryland, USA. 275 pp.

Kapetsky, J.M. & Aguilar-Manjarrez, J. 2004. Geographical Information Systems in aquaculture development and management from 1985 to 2002: an assessment. *In* Nishida, T., Kailola, P. and Hollingworth, C. eds. GIS/Spatial analyses in fishery and aquatic sciences (Vol 2.) Proceedings of the Second International Symposium on GIS/Spatial analyses in fishery and aquatic sciences. pp. 393-404. Fishery-Aquatic GIS Research Group. Kawagoe, Saitama, Japan. 733 pp.

Kapetsky, J.M. & Caddy, J.F. 1985. Applications of remote sensing to fisheries and aquaculture. FAO Report of the 11th Session of the Advisory Committee on Marine Resources Research, Supplement. FAO, Rome. FAO Fisheries Report, (338) Suppl.:37-48.

Kapetsky, J.M. McGregor, L. & Nanne E, H. 1987. *A geographical information system and satellite remote sensing to plan for aquaculture development: a FAO-UNDP/GRID cooperative study in Costa Rica.* FAO Fisheries Technical Paper No. 287. Rome, FAO. 51 pp.

Kapetsky, J.M. & Nath, S.S. 1997. A strategic assessment of the potential for freshwater fish farming in Latin America. *COPESCAL Technical Paper*. No. 10. Rome, FAO. 128 pp. (also available at http://www.fao.org/DOCREP/005/W5268E/W5268E00.HTM).

Kite-Powell, H., Hoagland, P., Jin, D. & Murray. K. 2003. Open ocean grow-out of finfish in New England: A bioeconmic model. In Pages 319-324. C.J. Bridger and Costa-Pierce B.A, (eds.). Open Ocean Aquaculture: From Research to Commercial Reality. The World Aquaculture Society. Baton Rouge, Louisiana, USA.

Kona Blue Water Farms 2003. Final Environmental Assessment For An Offshore Open Ocean Fish Farm Project Off Unualoha Point, Kona, Hawaii. Prepared for Land Division, Land and Natural Resources, Hawaii. 110 pp.

Langan, R. & Horton, F. 2003. Design, operation and economics of submerged longline mussel culture in the open ocean. Bulletin of the Aquaculture Association of Canada. 103-3: 11-20.

Legault, J.A. 1992. Using a geographic information system to evaluate the effects of shellfish closures on shellfish leases, aquaculture and habitat availability. Canadian Technical Report of Fisheries and Aquatic Sciences 1882E:1-10.

Leung, P.S. 2006. Multiple-criteria decision-making (MCDM) applications in fishery management. *Int. J. Environmental Technology and Management*, 6 (1/2): 96-110.

Loubersac, L., Prou, J. , Kerdreux, M. & Le Moine, O. 1997. Geomatics for the management of oyster culture leases and production. CoastGIS'97. In: D. Green, and G.Massie editors. Proceedings of the Second International Symposium on GIS and Computer Mapping for Coastal Zone Management. University of Aberdeen, Scotland. Aug. 29-31, 1997.

Macias-Rivero, J.C., Castillo y Rey, F. & Zurita, C.A. 2003. Zonas idóneas para el desarrollo de la acuicultura en el litoral andaluz. Dirección General de Pesca y Acuicultura, Consejería de Agricultura y Pesca, Junta de Andalucía. 43 p. y mapas.

Malczewski, J. 1999. GIS and Multicriteria Decision Analysis, Wiley, New York.

Malczewski,J.2006. Integrating multiple-criteria analysis and geographic information systems: the ordered weighted averaging (OWA) approach. *Int. J. Environmental Technology and Management*, 6 (1/2): 7-19.

Marine Aquaculture Task Force. 2007. Sustainable marine aquaculture: Fulfilling the promise; managing the risk. Marine Aquaculture Task Force, Takoma Park, MD, USA. 128 pp. (available at http://www.pewtrusts.com/pdf/Sustainable_Marine_Aquaculture_final_1_07.pdf)

Marine Policy Center, Woods Hole Oceanographic Institute. 2003. Improving the Regulatory Framework for Marine Aquaculture Regional Planning and Economic Decision-making. NOAA National Marine Aquaculture Initiative Final Report (available at http://www.lib.noaa.gov/docaqua/nmaimages2001/finrepwhoi.htm).

Martinez-Cordero, F. & Leung, P.S. 2004. Multicriteria decision making (MCDM) model for regional sustainable shrimp farming development in northwest Mexico. *Aquaculture Economics and Management.* 8 (3/4): 179-192.

National Office for Harmful Algal Blooms, Woods Hole Oceanographic Institution,Woods Hole, Massachusetts, USA. 2006. (available at http://www.whoi.edu/redtide/index.html).

Meaden, G. J. 2004. Challenges of using geographic information systems in aquatic environments. *In* Fisher, W. L. and Rahel, F.J. eds. Geographic information systems in fisheries. pp. 13-48. American Fisheries Society, Bethesda, Maryland, USA. 275 pp.

Meaden, G.J. & Do Chi, T. 1996. *Geographical information systems: applications to marine fisheries*, FAO Fisheries Technical Paper No. 356. Rome, FAO. 335 pp. (also available at http://www.fao.org/docrep/003/W0615E/W0615E00.HTM).

Meaden, G.J. & Kapetsky, J.M. 1991. *Geographical information systems and remote sensing in inland fisheries and aquaculture.* FAO Fisheries Technical Paper *No.* 318. Rome, FAO. 262 pp. (also available at http://www.fao.org/DOCREP/003/T0446E/T0446E00.HTM).

Mooneyhan, W. 1985. Determining aquaculture development potential via remote sensing and spatial modelling. Applications of remote sensing to aquaculture and inland fisheries. Report of the ninth UN/FAO international training course in co-operation with the Government of Italy. FAO Rome RSC Series 27:217-247.

Muir, J., 2004, Offshore Mariculture System Options. Lecture delivered at the CIHEAM Advanced Course on Offshore Mariculture, Zaragoza (Spain), 17-22 May 2004 (available at http://www.easonline.org/agenda/en/description.asp?id=264).

National Geophysical Data Center. 2006. NOAA Satellite and Information Service (available at http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html).

National Oceanographic Data Center, NOAA. 2005. Pathfinder Version 5.0. Sea Surface Temperature Climatologies (available at ftp://data.nodc.noaa.gov/pub/data.nodc/pathfinder/Version5.0_Climatologies/README.txt).

National Oceanographic Data Center, NOAA. 2004. Climatologies for the Coral Atlas Project (available at ftp://data.nodc.noaa.gov/pub/data.nodc/pathfinder/CoralAtlas/Information_on_Climatologies.txt).

Nath,S. S., Bolte, J. P., Ross, L. G. & Aguilar-Manjarrez, J. 2000. Applications of Geographical Information Systems (GIS) for spatial decision support in aquaculture. *Aquaculture Engineering* 23:233–278.

Newell, C.R. 2001. Sustainable mussel culture: A millennial perspective. Bulletin of the Aquaculture Association of Canada. 101-2:15-21.

Newell, C.R. 2003. Shellfish aquaculture and carrying capacity. Report of a Task Force Meeting. Maine Department of Marine Resources. 5pp. (available at http://www.maine.gov/dmr/aquaculture/aqtaskforce/aqtfwalpole.htm).

Nishida, T., Kailola, P. & Holliingworth, C. eds. 2001. Proceedings of the First International Symposium on GIS in Fishery Science. Fishery-Aquatic GIS Research Group. Kawagoe, Saitama, Japan. 486 pp.

Nishida, T., Kailola, P. & Holliingworth, C. eds. 2004. GIS/Spatial analyses in fishery and aquatic sciences (Vol 2.) Proceedings of the Second International Symposium on GIS/Spatial Analyses in Fishery and Aquatic Sciences. Fishery-Aquatic GIS Research Group. Kawagoe, Saitama, Japan. 733 pp.

Nishida, T., Kailola, P. & Holliingworth, C. eds. (in press). Proceedings of the Third International Symposium on GIS in Fishery Science. Fishery-Aquatic GIS Research Group. Kawagoe, Saitama, Japan.

Office of Coast Survey. 2006. Exclusive Economic Zone. NOAA (available at http://nauticalcharts.noaa.gov/csdl/EEZ.HTM).

Pattison, D., dos Reis, D. & Hamilton, S. 2004. An inventory of GIS-Based Decision Support Tools for MPAs. Prepared by the National Marine Protected Areas Center in cooperation with the National Oceanic and Atmospheric Administration Coastal Services Center. 14 pp (available at http://www.mpa.gov).

Pavasovic, S. 2004. GIS-tool for site suitability analysis: Example of marine aquaculture. ECO-IMAGINE Virtual Permanent Conference (European Conferences and forum for Integrated Coastal Management and Geo-Information Research) / GI and GIS for ICM, Seville (Spain). (available at http://www.gisig.it/eco-imagine/VirtualPConference/siviglia-proceedings/pres entations.htm).

Pérez, O.M. 2003. GIS-based models for optimisation of marine cage aquaculture in Tenerife, Canary Islands. Institute of Aquaculture, University of Stirling, Scotland, UK. (Ph.D. Thesis).

Pérez, O.M., Muir, J.M. & Ross, L.G. 2000. Spatial modelling of aquaculture related development, poverty and needs issues (preliminary study). University Of Stirling. 42 pp. (available at http://www.aquaculture.stir.ac.uk/GISAP/gis-group/dfid.php).

Pérez, O.M., Ross, L.G., Telfer, T.C. & Beveridge, M.C. 2002. Geographical information systems (GIS) as a simple tool for modelling waste distribution under marine fish cages. Estuarine Coastal and Shelf Science 54:761-768.

Pérez, O.M., Telfer, T.C. & Ross, L.G. 2003a. On the calculation of wave climate for offshore cage culture site selection: a case study in Tenerife (Canary Islands). Aquacultural Engineering, 29: 1-21.

Pérez, O.M., Telfer, T.C. & Ross, L.G. 2003b. Use of GIS-Based Models for Integrating and Developing Marine Fish Cages within the Tourism Industry in Tenerife (Canary Islands). Coastal Management, 31:355–366.

Pérez, O.M., Telfer, T.C. & Ross, L.G. 2005. Geographical information systems-based models for offshore floating marine fish cage aquaculture site selection in Tenerife, Canary Islands. Aquaculture Research 36(10), 946-961.

Populus, J., Loubersac, L., Prou, J, Kerdreux, M. & Le Moine, O. 1997. Geomatics for the management of oyster culture leases and production. CoastGIS'97. In: D. Green, and Massie, G. eds. Proceedings of the Second International Symposium on GIS and Computer Mapping for Coastal Zone Management. University of Aberdeen, Scotland. Aug. 29-31, 1997.

Rodriguez-Benito, C., Haag, C. & Alvial, A. 2004. Implementation of new technologies to monitor phytoplankton blooms in the south of Chile. Proceedings of the MERIS User Workshop, Frascati, Italy, 10 – 13 November 2003 (ESA SP-549, May 2004).

Ross, L.G., 1998. The use of Geographical Information Systems in Aquaculture: A Review. Paper presented at I Congreso Nacional de Limnología, Michoacán, México. November 1998.

Ross, L.G., Mendoza, E.A.Q. & Beveridge, M.C. 1993. The application of geographical information systems to site selection for coastal aquaculture: an example based on salmonid cage culture. Aquaculture 112:165-178.

Ryan, J. 2004. Farming the deep blue. Bord Iasscaigh Mhara and Irish Marine Institute. Ireland. 67 pp.

Saaty, T.L. 1980. The Analytic Hierarchy Process. McGraw-Hill, New York.

Saaty, T.L. 2006. Fundamentals of the analytic network process — Dependence and feedback in decision-making with a single network. *Journal of Systems Science and Systems Engineering.* Publisher Systems Engineering Society of China, co-published with Springer-Verlag GmbH. 13 (2): 129-157.

Salam, A. Md. 2000. GIS modelling of coastal aquaculture development in Khulna district, Sunderbans, Bangladesh. Institute of Aquaculture, University of Stirling, Scotland, UK. p400. (Ph.D. Thesis).

Saxby, S.A. 2002. A review of food availability, sea water characteristics and bivalve growth performance at coastal culture sites in temperate and warm temperate regions of the world. Department of Fisheries, Government of Western Australia. Fisheries Research Report 132. 43 pp.

Scott, P.C. 2004. Aquaculture development interactions in Sepetiba Bay, Rio de Janeiro, Brazil. A GIS study.Institute of Aquaculture, University of Stirling, Scotland, UK. (Ph.D. Thesis).

Scott, P.C. & Ross, L.G. 1998. O potencial da mitilicultura na Baía de Sepetiba. Panorama da Aquicultura 8(49):13-19.

Scott, P.C., Vianna, L.F. & de C. Mathias, M.A., 2002. Diagnostico da cadeia aquicola para o desenvolvimento da atividade no Estado do Rio de Janeiro. Panorama da Aquicultura 12(71):15-25.

Scottish Executive 2000. Final Report of the Joint Government/Industry Working Group on Infectious Salmon Anaemia (ISA) in Scotland. Scottish Executive, Aberdeen, Scotland. 142 pp.

Scottish Salmon Producers' Organization. 2005. Code of Good Practice for Scottish Finfish Aquaculture (available at http://www.scottishsalmon.co.uk/aboutus/codes.asp).

Servicio de Pesca y Acuicultura. 2000. Acuicultura marina en la región de Murcia: Identificación de zonas aptas para el cultivo. Dirección General de Ganadería y Pesca, Consejería de Agricultura, Acuicultura y Medio Ambiente, Región de Murcia. Cartagena, España. 35p. + mapas.

Sylvia, G. & Anderson, J.L. 1993. An economic policy model for net-pen salmon farming. In: Hatch, U., Kinnnucn, H. (Eds.) Aquaculture: Models and Economics, Westview Press, Boulder, pp. 17-38.

Simpson, J.J. 1994. Remote sensing in fisheries: A tool for better management in the utilization of a renewable resource. *Canadian Journal of Fisheries and Aquatic Sciences* 51: 743-771.

Smith, G.F., Bruce, E.B. & Roach, D.G. 2001. Remote acoustic habitat assessment techniques used to characterize the quality and extent of oyster bottom in the Chesapeake Bay. Marine Geodesy, 24(3): 171-189.

Smith. G.F. & Greenhawk, K.N. 1996. Morphological differentiation of the fringing and patch oyster reef types in Chesapeake Bay: A comparative evaluation. *Journal of Shellfish Research* 15: 522.

Smith, G.F., Greenhawk, K.N. & Homer, M.L. 1997. Chesapeake Bay oyster reef - An examination of resource loss due to sedimentation. *Journal of Shellfish Research* 16:275.

Smith, G.F., Greenhawk, K.N., Bruce, E.B., Roach, D.G. & Jordan, S.J. 2001. A digital presentation of the Maryland oyster habitat and associated bottom types in the Chesapeake Bay (1974-1983). *Journal of Shellfish Research*, 20(1): 197-206.

Smith, G.F. & Jordan, S.J. 1993. Utilization of a geographical information system (GIS) for the timely monitoring of oyster population and disease parameters in Maryland's Chesapeake Bay. *Journal of Shellfish Research* 12: 130.

Smith, G.F., Jordan, S.J. & Greenhawk, K.N. 1994. An oyster management information system: Integrating biological, physical, and geographical dimensions. *Journal of Shellfish Research* 13:284.

Smith, G.F., Roach, D.G. & Bruce, E.B. 2002. The location, composition, and origin of oyster bars in mesohaline Chesapeake Bay. Estuarine, Coastal and Shelf Science 56: 391-409.

Soletchnik, P., Le Moine, O., Faury, N., Razet, D., Geairon, P., & Goulletquer, P. 1999. Summer mortality of the oyster in the Bay Marennes-Oleron: Spatial variability of environment and biology using a geographical information system (GIS). *Aquatic Living Resources Ressources Vivantes Aquatique* 12:131-143.

Soares de Souza, E.F. 2003. FAO Technical Cooperation Programme Project. Small-scale seaweed farming in Northeast Brazil. TCP/BRA/0065. Field Document. FAO, Rome.

Stickney, R.R., Costa-Pierce, B., Baltz, D.M., Drawbridge, M., Grimes, C., Phillips, S. & Swann, D.L. 2006. Toward sustainable open ocean aquaculture in the United States of America. *Fisheries* 31(12): 607-610.

Subasinghe, R.P., Bueno, P., Phillips, M.J., Hough, C., McGladdery, S.E. & Arthur, J.E. (eds.) 2000. Aquaculture in the Third Millennium - Technical Proceedings of the Conference on Aquaculture in the Third Millennium, Bangkok, Thailand. 20-25 February 2000. NACA, Bangkok and FAO, Rome. 471pp. (also available at http://www.fao.org/fi/meetings/aq2000/tech_proc/third_mill.asp).

Taconet, M. & Bensch, A. 2000. Towards the use of Geographic Information Systems as a decision support tool for the management of Mediterranean fisheries. COPEMED. GCP/REM/057/SPA. Informes y Estudios No. 4. (pages not numbered).

Tiensongrussmee, B. Pontjoprawiro, S. & Mintarjo, K. 1988. Seafarming resources map. Seafarming Development Project, INS/81/008/Manual/7. FAO, Jarkata, Indonesia. 109 pp.

Travaglia, C. & Appelkamp, C. 1985. Applications of Remote Sensing to Aquaculture and Inland Fisheries. Ninth UN/FAO International Training Course in Co-operation with the Government of Italy. Rome, Italy, 10-28 September 1984. RSC SER., No. 27. Rome, FAO. 301 pp.

Travaglia, C., Profeti, G., Aguilar-Manjarrez, J. & Lopez, N. A. 2004. *Mapping Coastal Aquaculture and Fisheries Structures by Satellite Imaging Radar: Case Study of the Lingayen Gulf, the Philippines*. FAO Fisheries Technical Paper. No. 459. Rome, FAO. 45 pp. (also available at http://www.fao.org/docrep/007/y5319e/y5319e00.htm).

Valvanis, V.D. 2002. Geographic Information Systems in Oceanography and Fisheries. Taylor and Francis, London.

van der Woerd, H.J., Blauw, A., Pasterkamp, R., Tatman, S., Laanem, S. & Peperzak, L. 2005. Integrated spatial and spectral characterization of harmful algal blooms in Dutch coastal waters. Report 05/09. Institute for Environmental Studies, Amsterdam, The Netherlands. 59 pp.

Vincenzi S., Caramori, G., Rossi, R. & De Leo, G.A. 2006. A GIS-based habitat suitability model for commercial yield estimation of *Tapes philippinarum* in a Mediterranean coastal lagoon (Sacca di Goro, Italy). *Ecological Modelling* 193 (2006) 90–104.

Vincenzi S., Caramori, G., Rossi, R. & De Leo, G.A. (in press). Estimating clam yield potential in the Sacca di Goro lagoon (Italy) by using a two-part conditional model. Aquaculture.

Vincenzi S., Caramori, G., Rossi, R. & De Leo, G.A. (in prep). Implications of three habitat 1suitability models for commercial yield estimation of *Tapes philippinarum* in a North Adriatic coastal lagoon (Sacca di Goro, Italy).

Ueng, Ping-Sheng, Yu, Shyi-Liang, Tzeng, Jiann-Jang, & Ou, Ching-Hsiewn. 2001. The effect of water temperature on growth rate of cobia *Rachycentron canadum* in Penghu, Taiwan. 6th Asian Fisheries Forum Book of Abstracts. 252 pp.

Wright, D.J., ed. 2002. Undersea with GIS. ESRI Press, Redlands, California, USA. 253 pp.

Wright, D.J. & Bartlett, D.J., Eds. 2000, Marine and Coastal Geographical Information Systems, Research Monographs in Geographical Information Science, Taylor and Francis, London. 320 pp.

Young, L., Helsley, C. , Ummoto, K., Merrifield, M., Tasaka, C., Kaiokamale, L., Takahashi, K., Pichaya, V. & Shen, C. 2003. Aquaculture site identification in Hawaii using GIS. *INFOFISH International* (6): 13-16.

The objective of this document is to illustrate the ways in which Geographic Information Systems (GIS), remote sensing and mapping can play a role in the development and management of marine aquaculture. The perspective is global. The approach is to employ example applications that have been aimed at resolving many of the important issues in marine aquaculture.

The underlying purpose is to stimulate the interest of individuals in the government, industry and educational sectors of marine aquaculture to make more effective use of these tools. A brief introduction to spatial tools and their use in the marine fisheries sector precedes the example applications. The most recent applications have been selected to be indicative of the state of the art, allowing readers to make their own assessments of the benefits and limitations of use of these tools in their own disciplines.

The applications are organized issue-wise along the main streams of marine aquaculture: culture of fishes in cages, culture of shellfishes and culture of marine plants. A case study is included that illustrates how freely downloadable data can be used to estimate marine aquaculture potential. Because the ultimate purpose of GIS is to aid decision making, a section on decision support tools is included.

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