Annex 1

Overview of the spatial analyses and data sources

This annex briefly describes the processing steps used to create the results of the spatial analyses presented in this technical paper.

1. Hardware and software

The GIS software used in this study was Manifold (CDA International Ltd.) and ArcGIS 9.3 (ESRI). Manifold, versions up to 8.0.27, was used because it is a very affordable (currently about one-fifth of the cost of the most widely used GIS software) but fully functional GIS. ArcGIS 9.3 was used to prepare the raw data and to perform more complex analysis.

The text below describes the conceptual steps necessary to replicate the analysis described in this technical paper. Readers should be aware that most of the ArcGIS analysis could not be done with the standard ArcGIS tools, and, therefore, required custom VBA (Visual Basic for Applications) functions (i.e. codes) were required to conduct the analysis. The VBA computer codes written for this technical paper are available upon request from the authors of this technical paper, but they will only be useful to readers using ArcGIS with VBA installed and licensed.

2. Spatial data

Spatial data used for this technical paper were: (i) exclusive economic zones (EEZ); (ii) bathymetry; (iii) current speeds; (iv) world ports; (v) sea surface temperature (SST); (vi) chlorophyll-*a*; (vii) marine protected areas; (viii) Global Administrative Area from the GADM database; and (ix) geographic zones (see Table A1.1 for details).

All data sets used in this study are presented in Section 4 of this Annex and are available for download in FAO's GeoNetwork portal (www.fao.org/geonetwork).

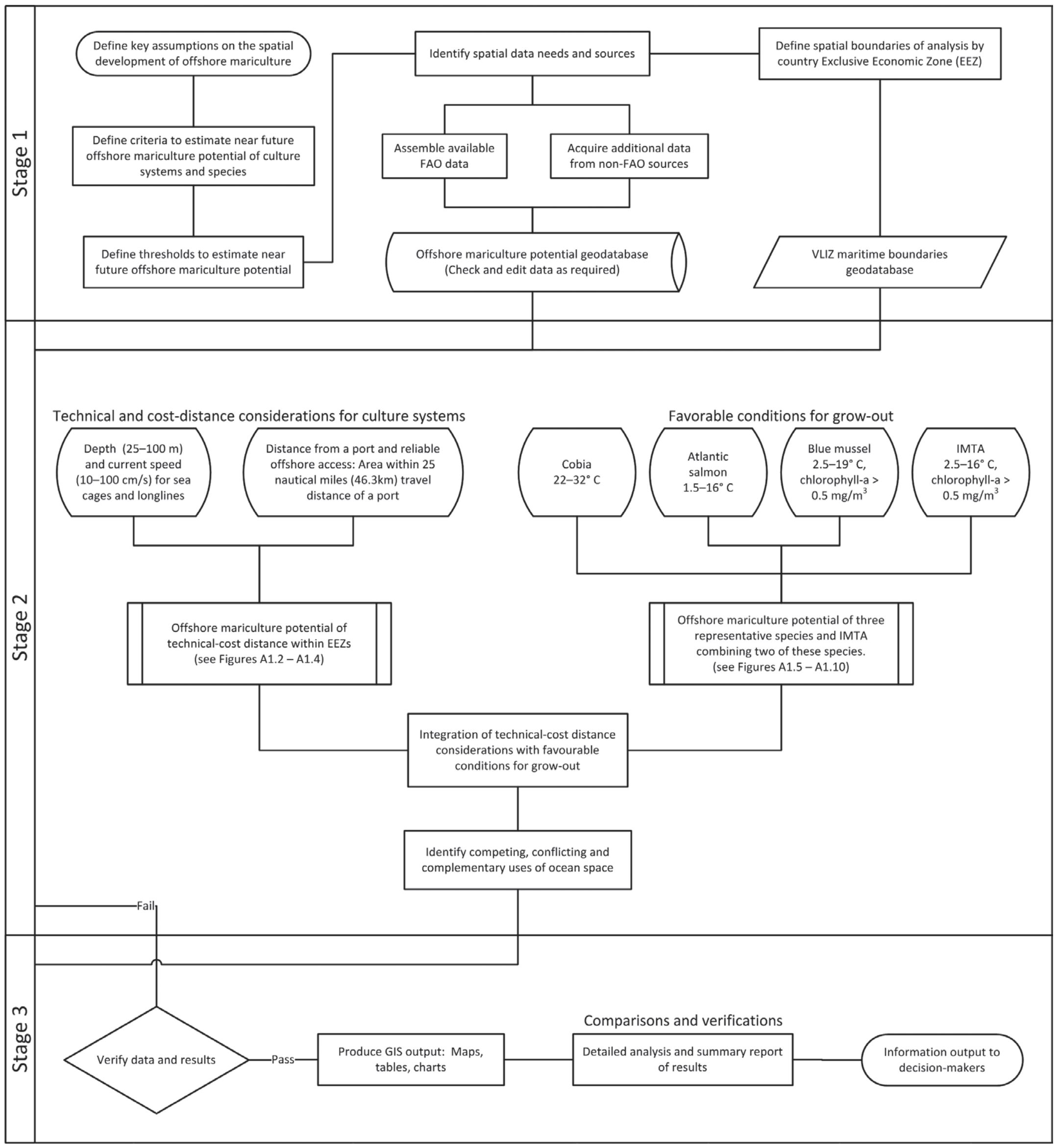
3. Spatial analysis

This study identifies areas that satisfy criteria for offshore mariculture development. The criteria include the suitability of depth and current speed for sea cages and longlines, and the temperatures favouring grow-out of representative species: cobia (*Rachycentron canadum*), Atlantic salmon (*Salmo salar*) and blue mussel (*Mytilus edulis*), as well as chlorophyll-*a* concentration for the last species.

There were two important limitations to this study. First, only already-digitized or computer-ready data could be used for the analysis to save costs, and second, because offshore mariculture potential is being predicted for areas where it largely does not yet exist, verification was limited to using the location of a few offshore fish farms and relied mainly on comparisons of offshore potential with existing inshore mariculture. Another limitation was that the data had to be comparable for all maritime countries. In overview, this study consisted of three major analytical stages (Figure A1.1):

(i) data preparation;
(ii) integration of data sets; and
(iii) verification.

FIGURE A1.1
Major analytical stages



Note: Fail acknowledges that verification could be incomplete, or in some cases fail.

Note: Areas with potential within EEZs, but presently outside of cost-effective areas for development were estimated by setting aside the cost-effective area for development (see Table 1, Criterion 4).

3.1 Data preparation

Various aspects of this analysis required analysing and processing data in both raster and vector formats. The general strategy with raster data was to do all analysis at the finest resolution of the data, and then to convert the final to vector format for further analysis. For example, if a particular analysis was required to identify regions that met thresholds using multiple rasters, then the new raster that was generated would have the same resolution as the finest resolution of the multiple input rasters. The new raster would then be converted to a polygon feature class[7] for further analysis.

[7] A polygon feature class is a geographic data set of polygonal vector objects (i.e. entities that cover an area, such as administrative units or analysis areas), plus associated attribute information for each polygon. Other examples of vector data sets include polyline feature classes (containing linear features such as roads or rivers) and point feature classes (containing such things as port locations).

EEZ boundaries to define the spatial limits for near-future offshore development

Exclusive economic zone boundaries were taken from the Flanders Marine Institute (Vlaams Instituut voor de Zee, or VLIZ) data, Version 5.

Depth and current speed to define the spatial limits on offshore cages and longlines

Regions suitable for offshore cages and longlines were defined according to current speed and depth (Figures A1.2–A1.3) based on data from manufacturers and mariculture practice (Table A1.2 (depth) and A1.3a (current speed).

FIGURE A1.2
Steps to define spatial limits on offshore cages and longlines based on depth and current speed

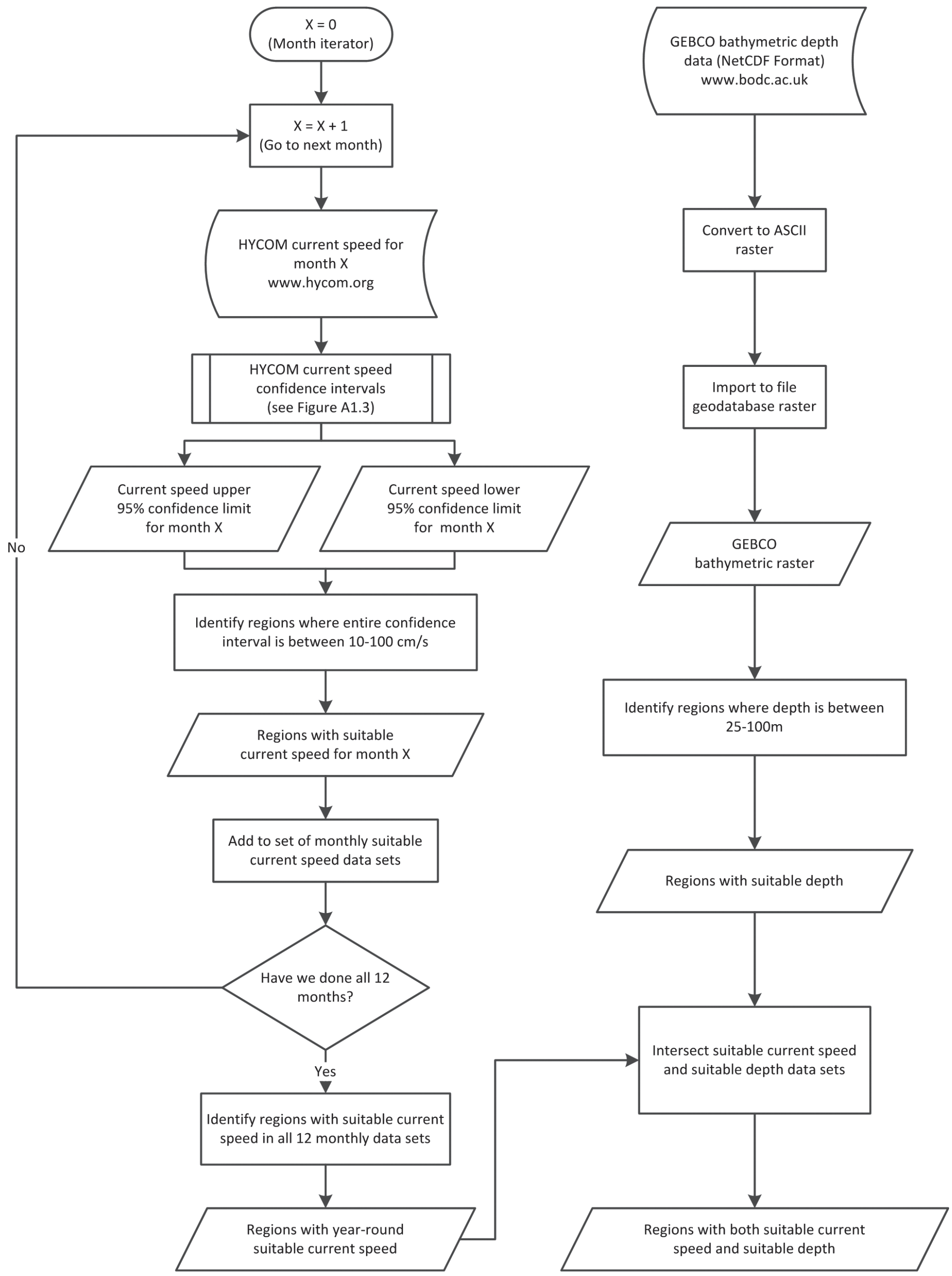
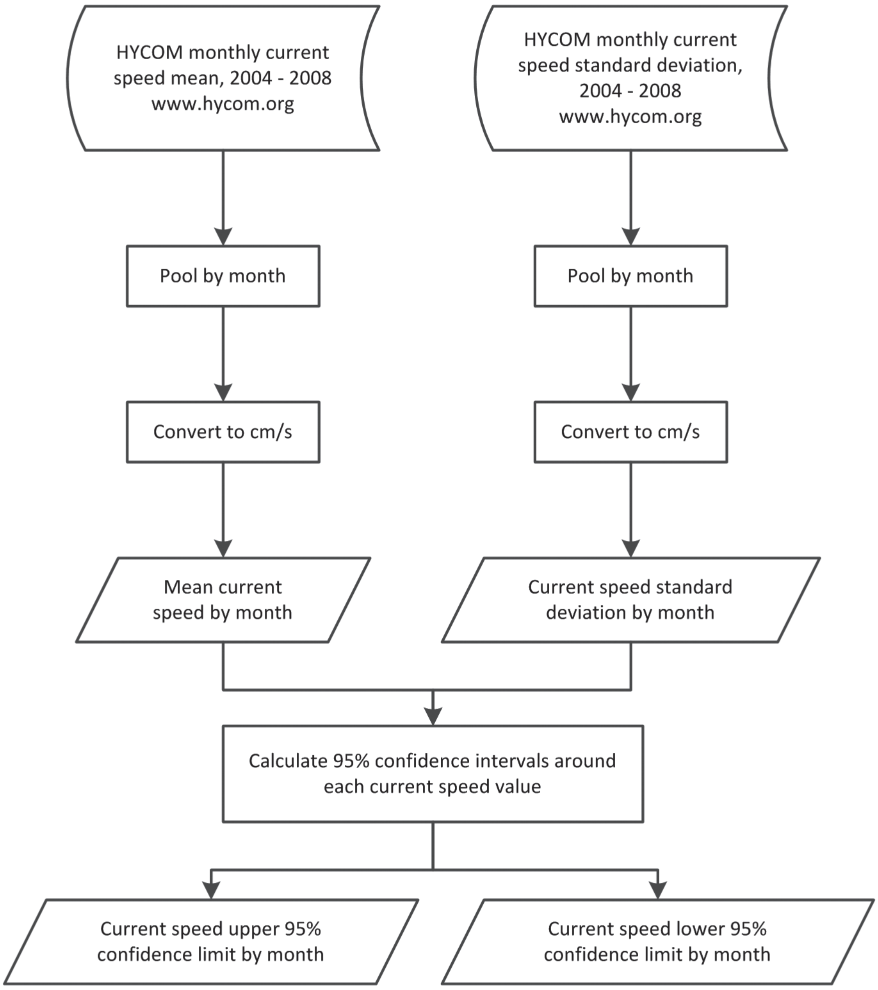


FIGURE A1.3
HYCOM current speed confidence intervals subprocess



Depth: bathymetric data were extracted from the 2008 version of General Bathymetric Chart of the Ocean (GEBCO), which is a raster data set with cell edge lengths of approximately 0.9 km. In all analyses using this bathymetric data, regions with depths in the desired ranges were converted to polygon feature classes for further analysis.

Horizontal cell size: the GEBCO bathymetric data had 43 200 columns covering 360 degrees of longitude (40 075 km equatorial circumference). This equals to 0.92766 km per cell width along the equator. This east-west distance decreases when moving towards the poles. The extreme north and south rows that actually had data were < 1 metre in width.

Vertical cell size: the GEBCO bathymetric data had 21 600 rows covering 180 degrees of latitude (20 004 km from the North Pole to South Pole), equal to 0.92611 km per cell. This north-south distance is constant for all cells.

Current speed: the current speed data (from HYCOM, representing current speed at 30 m depth) included separate monthly data sets over a 5-year period from 2004 to 2008. Therefore, data were pooled by month before calculating the confidence intervals. Note: the original HYCOM current speed units are in metres per second, so these values were converted to centimetres per second for the final threshold analysis. Summarized monthly mean, standard deviation and upper/lower 95 percent confidence limits for current speed were calculated as follows:

Pooled Monthly Mean $\bar{x} = \dfrac{\sum_{i=2004}^{2008} \bar{x}_i N_i}{\sum_{i=2004}^{2008} N_i}$

where:

$\bar{x}_i$ = mean observed value for the month

N_i = number of days in month

i = Each month summed over 5-year period (2004 - 2008).

Pooled Monthly Standard Deviation $\sigma = \sqrt{\dfrac{\sum_{i=2004}^{2008} (N_i - 1)s^2}{\sum_{i=2004}^{2008} (N_i - 1)}}$

where:

s_i = standard deviation for the month

N_i = number of days in month

i = Each month summed over 5-year period (2004 - 2008).

95% Confidence Limits $= \bar{x} \pm t_{(0.975,N-1)} \dfrac{s}{\sqrt{N}}$

where:

$\bar{x}$ = pooled mean current speed for this month, combined over 5-year period

$t_{(0.975,N-1)}$ = critical value from t distribution at $N-1$ degrees of freedom

N = Number of days in pooled mean, combined over 5-year period

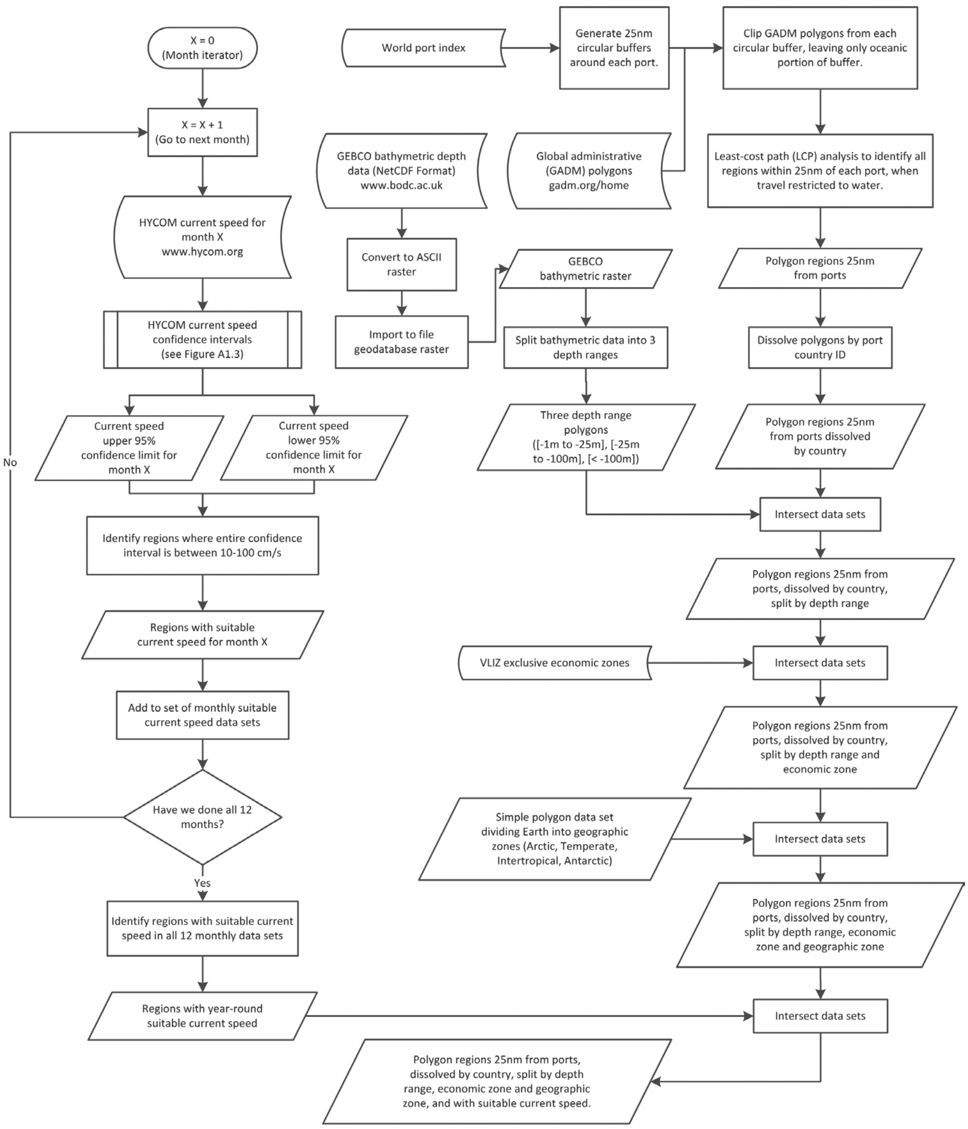
Horizontal cell size: HYCOM current speed data had 4 500 columns covering 360 degrees longitude (40 075 km equatorial circumference). This equals 8.90556 km per cell width along the equator. This east-west distance decreases when moving towards the poles. The extreme north and south rows that actually had data were < 2 km in width.

Vertical cell size: HYCOM current speed had 2 100 rows covering approximately 168 degrees latitude (~18,665 km from North Pole to –78°), equal to 8.88810 km per cell. This north-south distance is constant for all cells.

Distance from a port and reliable access to offshore spatially define the cost-effective area for offshore mariculture development

Cost-effective areas around ports: several steps were conducted to identify regions that were within 25 nm (46.3 km) of a port, intersected with depth range, current speed and VLIZ exclusive economic zone (Figure A1.4).

FIGURE A1.4
Steps to define cost-effective areas around ports



- Beginning with the 2009 World Port Index, 25 nm (46.3 km) buffer circles were first created around each port location using a custom VBA function. This function creates circles with 180 vertices distributed every 2° around the circle. Each vertex is created a specified distance and bearing from the port, and the new vertex locations are calculated accurately over the curved surface of the planet spheroid using spherical trigonometric functions so that the circles are undistorted by any projection issues.
- This study was only interested in the marine portion of the port buffers, so all land portions were clipped off based on Global Administrative Areas (GADM) polygons.
- This study was only interested in the portion of the port buffers that were within 25 nm travel distance from the ports, so the port buffers were further clipped to this region using a custom VBA function to create a cost-distance raster over each GADM-clipped port buffer polygon. This function calculates the cumulative distance from the port location, where travel is restricted to only the water. Note: this function is reasonably accurate but not perfect. Because of how cost-

distance functions work with raster surfaces, the final data set correctly identifies all locations within approximately 23.5 nm (43.5 km) of the port. It correctly identifies approximately half the locations between 23.5 and 25 nm of the port, and it incorrectly identifies approximately half the locations between 25 and 25.5 nm of the port. Therefore, there is some uncertainty about the area between 23.5 and 25.5 nm of the port. This problem is inherent in raster-based cost-distance algorithms and is unavoidable.

- The port buffer feature class was then intersected with GEBCO-derived Depth Range polygons (–1 m to –25 m), (–25 m to –100 m), (< –100 m).
- Finally, the port buffer feature class was intersected with VLIZ exclusive economic zone polygons.
- This final feature class reflects only maritime areas within 25 nm travel distance of ports, combined by country, and split by depth range and EEZ.

Eventually, the final feature class was intersected with areas favourable for the grow-out of the three species and integrated multitrophic aquaculture (IMTA).

Offshore mariculture potential of three representative species and IMTA of two of them spatially defined by environments favourable for grow-out

Chlorophyll-*a*, sea surface temperature and current speed: the raw data for chlorophyll-*a* (CHL2), sea surface temperature (SST) and current speed (CS) included mean values, number of observations and standard deviations per cell in raster format. Using a confidence level of $\alpha = 0.05$, these original rasters were used to generate 95 percent confidence intervals around the mean values. A location would be considered to fall within a threshold if the full confidence interval around the observed value at that location was completely within the upper and lower threshold values. For example, the temperature threshold for cobia was 22–32 °C. A location would only be considered to fall within this temperature range if both the lower confidence limit at that location was ≥ 22° and the upper confidence limit was ≤ 32°. Steps for identifying suitable regions for cobia, Atlantic salmon, blue mussel and IMTA are illustrated in Figures A1.5–A1.10.

FIGURE A1.5
Steps to define regions favorable for cobia grow-out

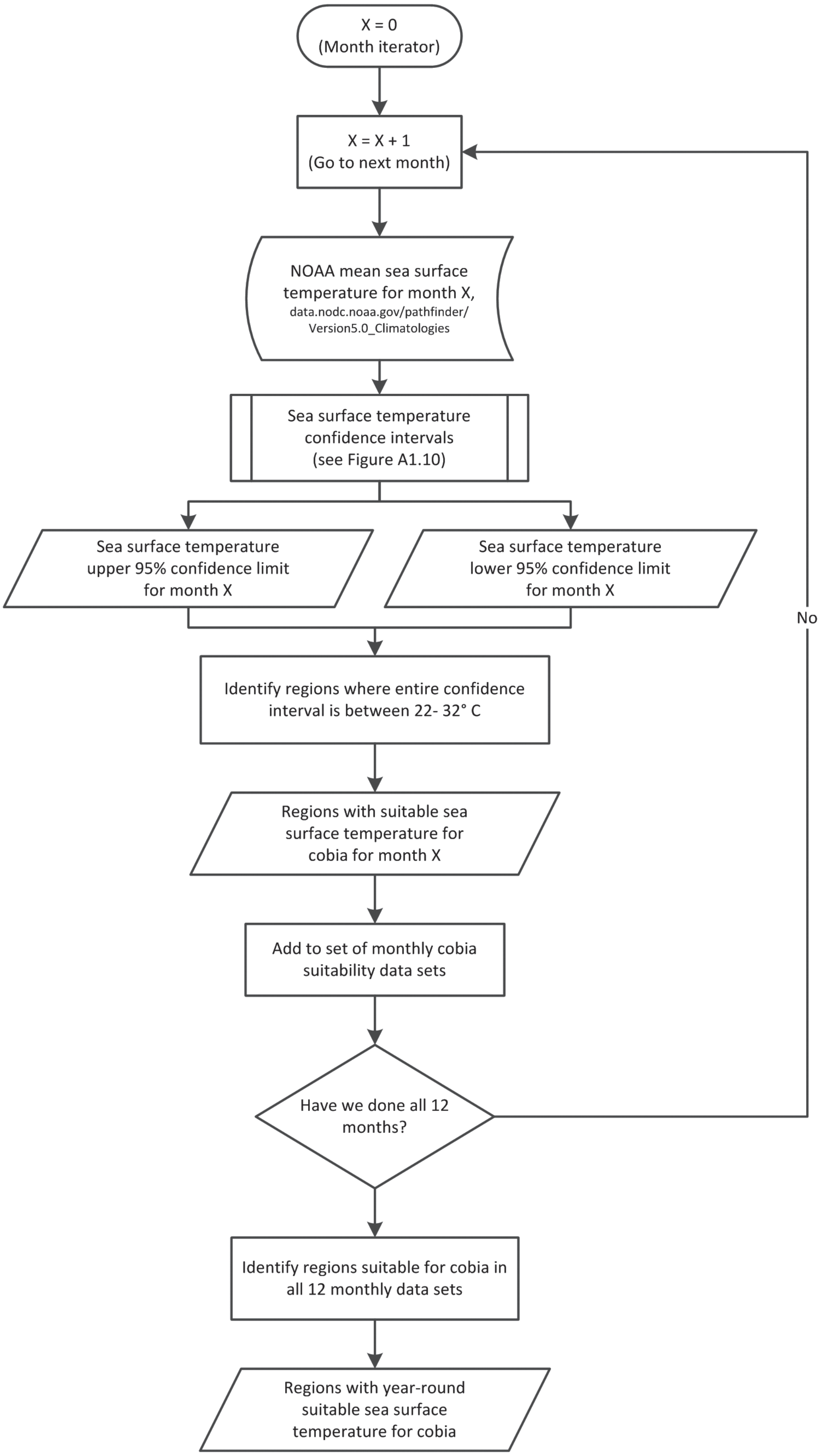


FIGURE A1.6
Steps to define regions favorable for grow-out of Atlantic salmon

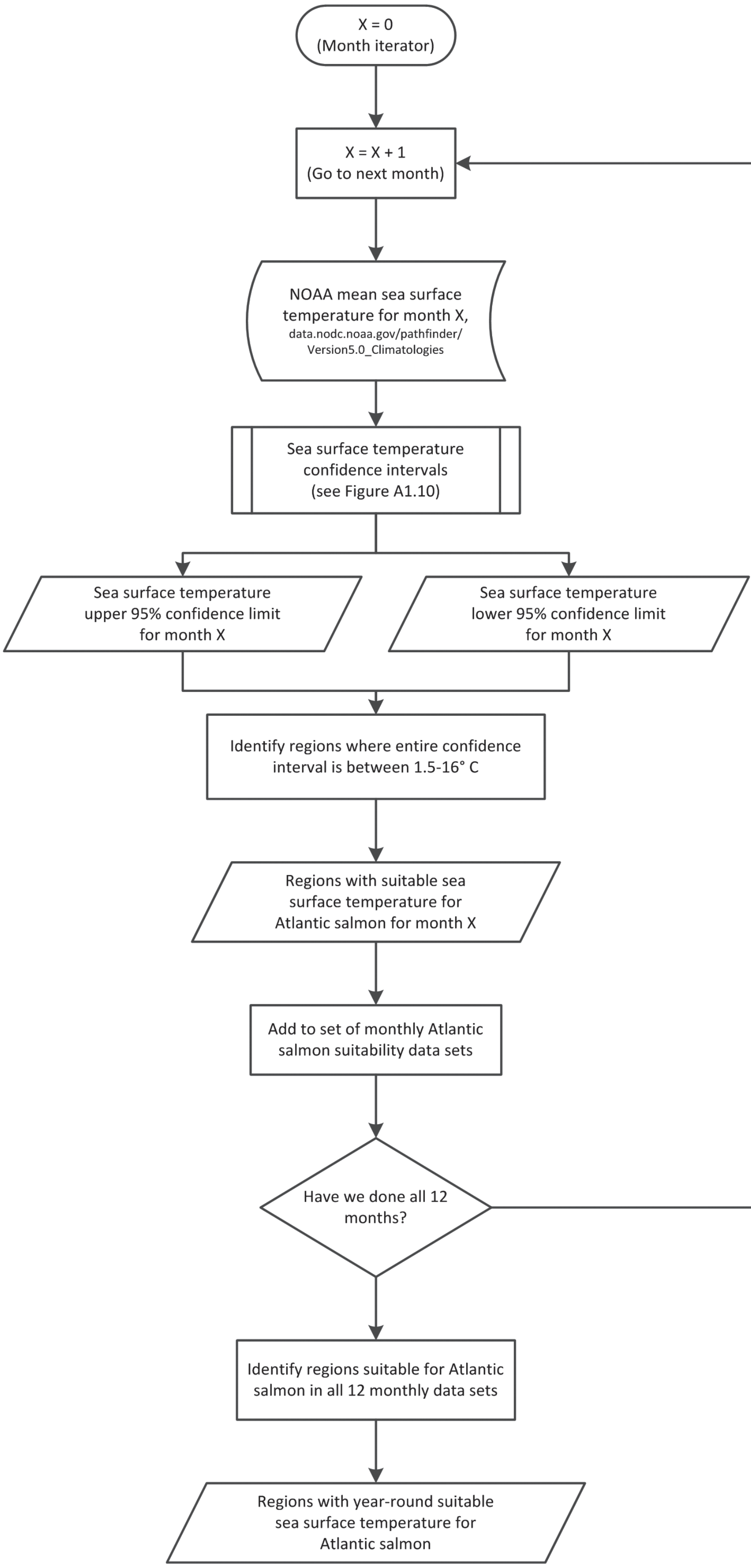


FIGURE A1.7
Steps to define regions favorable for grow-out of blue mussel

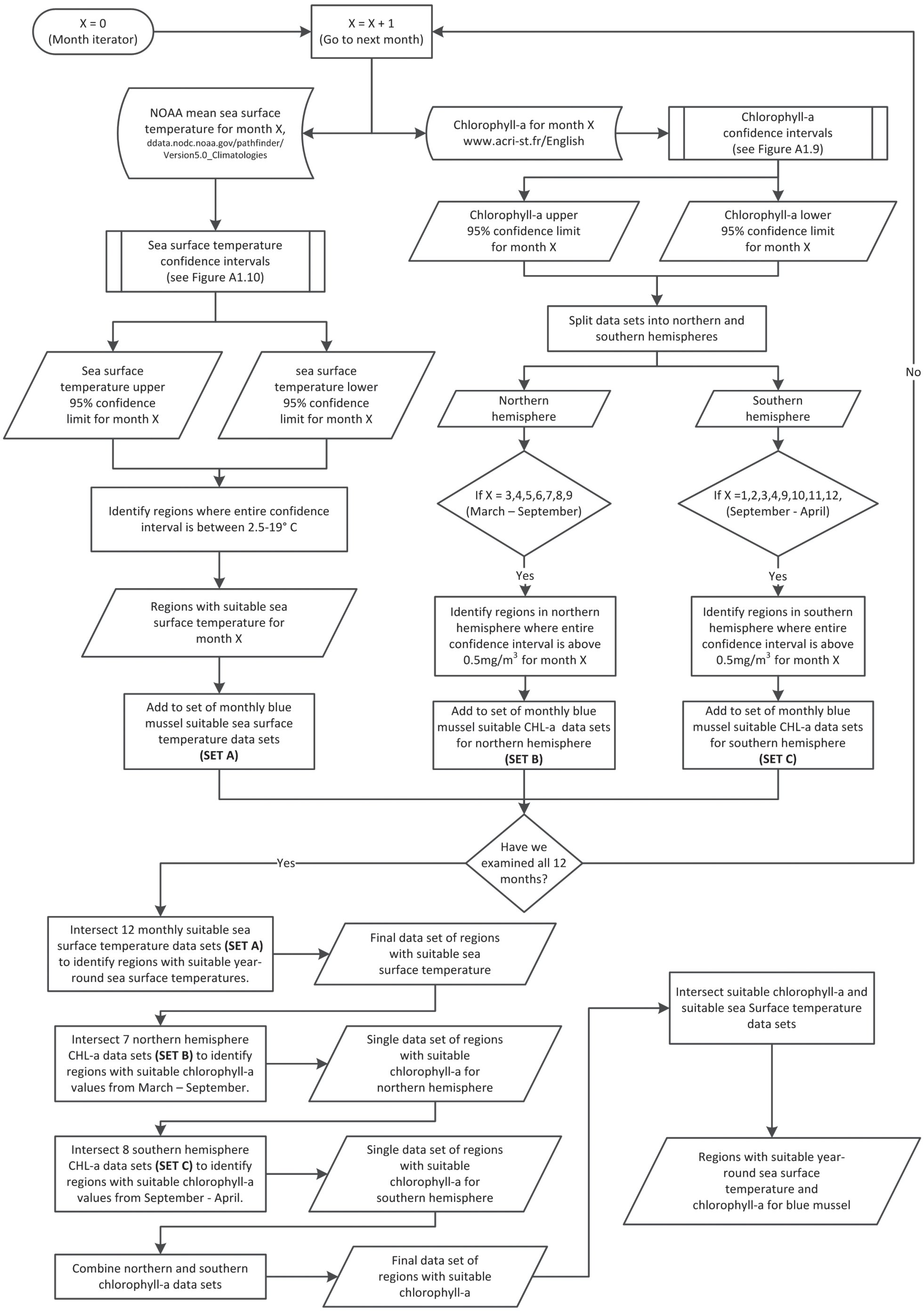


FIGURE A1.8
Steps to define regions favorable for grow-out of Integrated Multi-Trophic Aquaculture (IMTA)

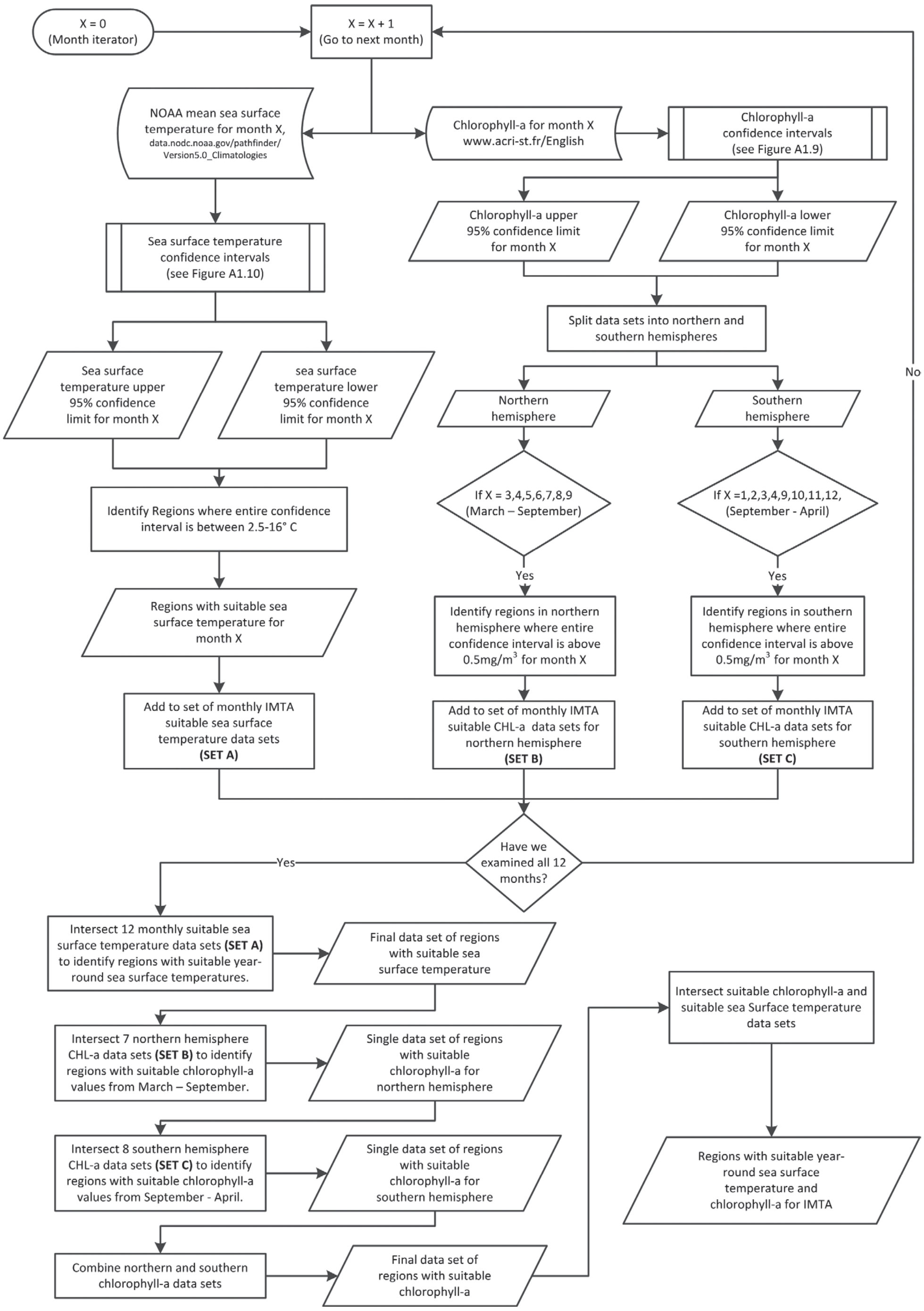


FIGURE A1.9
Chlorophyll-*a* confidence intervals subprocess

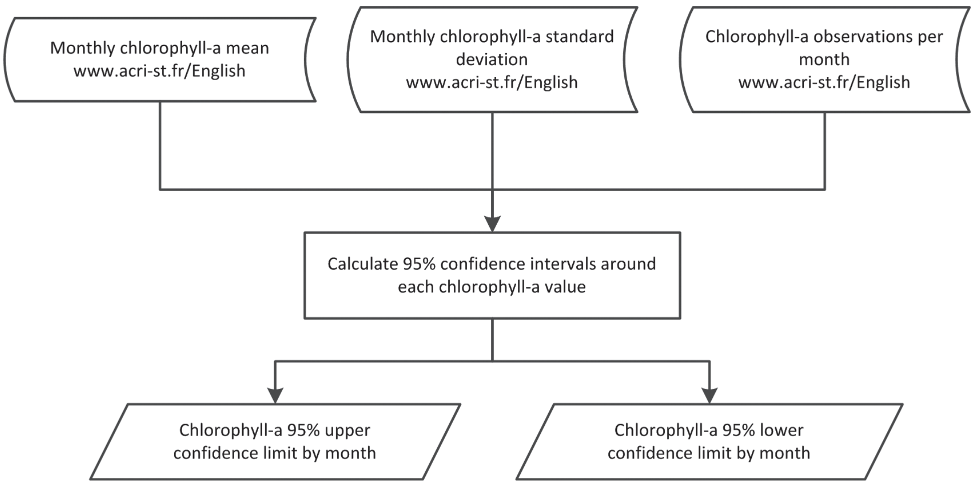
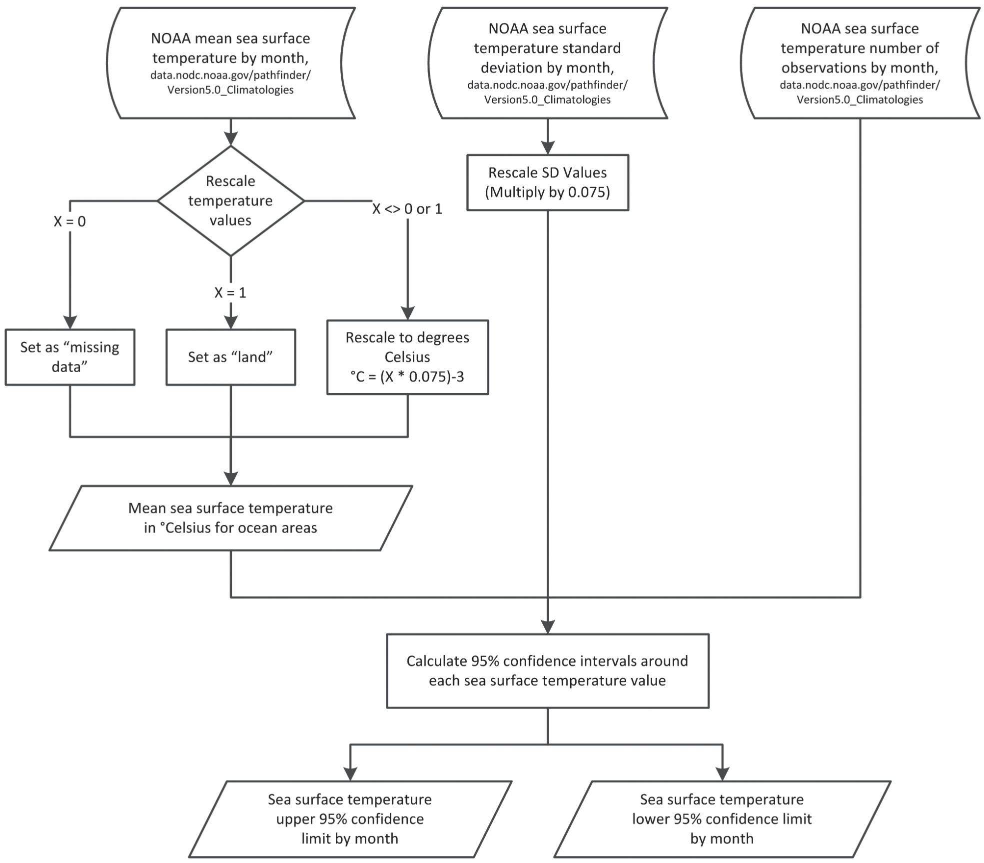


FIGURE A1.10
Sea surface temperature confidence intervals subprocess



CHL2 data was often unavailable at extreme latitudes in the colder months of the year, which complicated the task of identifying areas that met CHL2 thresholds. Therefore, analyses of CHL2 were done both seasonally and by the full year. In the Northern Hemisphere, seasonal data sets were calculated that met threshold requirements for the combined months of March, April, May, June, July, August and September. In the Southern Hemisphere, data sets were calculated that met threshold requirements for the combined months of September, October, November, December, January, February, March and April. These monthly data sets are the monthly averages for the years 2003–2009 (i.e. the "March" data represents the average CHL2 of all the months of March from 2003 through 2009). The final analysis only used the seasonal CHL2 data sets.

The CHL2, CS, SST and bathymetry data were in raster format at different resolutions. The CS had cell edge lengths of approximately 8.9 km, SST cell sizes were ~4.9 km, and CHL2 cell sizes were ~4.6 km. When identifying regions that met various combinations of CHL2, CS and SST thresholds, the finest resolution data set was used to define the resolution of the final raster. For example, an analysis that incorporated both CS and SST rasters would produce a raster with a cell size equal to the SST data because SST had the finest resolution. Bathymetry was at the highest resolution (~0.9 km) and was always converted to a vector polygon feature class of polygons meeting various depth thresholds before additional analysis.

After deriving a final raster delineating all areas that met some combination of thresholds, this final raster was then converted to a polygon feature class for further analysis.

Sea surface temperature: the sea surface temperature data were available as monthly values and, therefore, did not require pooling any data across years. However, to convert them to degrees Celsius, they needed to be rescaled according to the following formula:

True Sea Surface (SST) = [Original SST from HDF files) * 0.075] - 3

Furthermore, original SST values of 1 indicated that they were on land, and values of 0 indicated missing data, so these regions were excluded from the analysis.

95 percent confidence intervals around the mean SST value were calculated according to the following definition:

$$\text{95\% Confidence Limits} = \bar{x} \pm t_{(0.975,N-1)} \frac{s}{\sqrt{N}}$$

where:

$\bar{x}$ = mean SST value for this month

$t_{(0.975,N-1)}$ = critical value from t distribution at $N-1$ degrees of freedom

N = Number of SST observations in month (typically between 1 and 34)

Horizontal cell size: sea surface temperature data had 8 192 columns covering 360 degrees longitude (40 075 km equatorial circumference). This equals to 4.89197 km per cell width along the equator. This east-west distance decreases when moving towards the poles. The extreme north and south rows that actually had data were < 1 km in width.

Vertical cell size: sea surface temperature had 4 096 rows covering 180 degrees latitude (20 004 km from the North Pole to South Pole), equal to 4.88379 km per cell. This north-south distance is constant for all cells.

Chlorophyll-*a*: the Chlorophyll-*a* data were available as monthly values and, therefore, did not require pooling of any data. The 95 percent confidence intervals were calculated according to the following definition:

$$\text{95\% Confidence Limits} = \bar{x} \pm t_{(0.975,N-1)} \frac{s}{\sqrt{N}}$$

where:

$\bar{x}$ = pooled mean for this month

$t_{(0.975,N-1)}$ = critical value from t distribution at $N-1$ degrees of freedom

N = Number of CHL2 observations in month

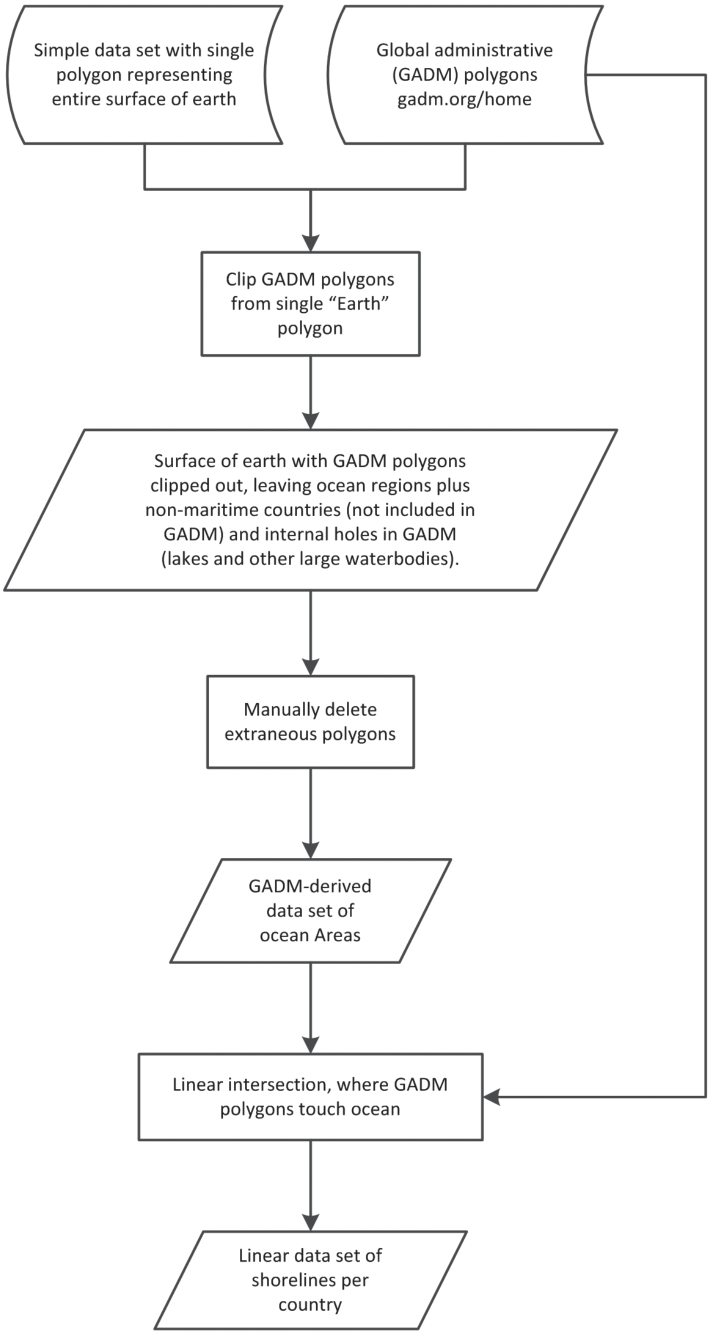
Horizontal cell size: chlorophyll-*a* data had 8 640 columns covering 360 degrees longitude (40 075 km equatorial circumference). This equals to 4.63831 km per cell width along the equator. This east-west distance decreases when moving towards the poles. The extreme north and south rows that actually had data were < 3 km in width.

Vertical cell size: chlorophyll-*a* had 4 320 rows covering 180 degrees latitude (20 004 km from the North Pole to the South Pole), equal to 4.63056 km per cell. This north-south distance is constant for all cells.

Marine protected areas: a data set of marine protected areas was derived from the World Dataset of Protected Areas. This data set was clipped so that it only represents marine areas, and was intersected with geographic zones.

Shorelines: the coastline length data were obtained from the Global Administrative Areas database of administrative boundaries (GADM, Version 1.0), available at www.gadm.org. The polyline data set of marine shorelines was derived by: (i) creating an "ocean" polygon data set by clipping out the GADM polygons from a general background polygon covering the entire earth; (ii) deleting all small polygons from the "ocean" data set that represented lakes or internal holes in the GADM data set; and then (iii) creating a coastline polyline data set by intersecting the GADM polygons with the ocean polygons. This last polyline data set is the linear intersection of all coastal countries with the oceans and, therefore, represents the coastline of all countries that face the ocean. This shorelines layer was essential to determine exactly how much shoreline each country has, and was intersected with other layers (such as the geographic zones data set) to determine how much shoreline lies within specific regions. The steps to generate shorelines are illustrated in Figure A1.11.

FIGURE A1.11
Steps to define coastlines



3.2 Integration of data sets

The compiled spatial data were used in two ways: (i) to identify all of the areas meeting the thresholds associated with each criterion; and (ii) to estimate temperatures and chlorophyll-*a* concentrations at specific mariculture locations. This approach also allowed these suitability thresholds to be compared with temperatures and chlorophyll-*a* concentrations actually experienced in inshore mariculture practice and to measure temperature and chlorophyll-*a* offshore of inshore mariculture locations.

Raster data sets were manipulated in ArcGIS 9.3 as described above, vectorized and imported to Manifold as shapefiles. In Manifold, the shapefiles became drawing (map) components in map projects. Each map project represented a separate analytical step (e.g. identifying the areas with depths suitable for cages and longlines). The output from each project consisted of a drawing and an associated table. Component outputs from individual projects were then sequentially integrated in subsequent projects (e.g. spatial integration of depths and current speeds) to obtain the results set out in Chapter 4. Topology overlay was the basic GIS tool used to spatially integrate the spatial data sets. Selection by query using spatial Structured Query Language was employed to organize the results into meaningful classes. Tables were exported to Microsoft Excel 2010, where the data were manipulated in pivot tables to provide the estimates of potential by EEZ and nation as surface area, which were then reported as tables and charts. Manifold also was used to arrange individual drawings into layers in maps and to add legends and labels to them, which were then exported as images that, in turn, became the map figures in this document.

The analysis conducted for this technical paper was primarily interested in cumulative areas that met various criteria (in which case slivers contributed very little to the cumulative total) and, therefore, the results were not significantly influenced by the potential effects of sliver[8] polygons. The data were also not the types that typically cause large numbers of slivers.

3.3 Comparisons of offshore potential with inshore mariculture locations and verification

Comparisons of predicted offshore potential with inshore mariculture practice at national and subnational levels and verifications at offshore mariculture sites

Three kinds of comparisons were made: (i) national-level comparisons of mariculture production based on FAO statistics (FAO Statistics and Information Branch of the Fisheries and Aquaculture Department, 2012) of the three species with national-level offshore mariculture potential of the species; (ii) known inshore mariculture locations of cobia, Atlantic salmon and blue mussel, obtained through a literature review, contacts with government entities in British Columbia, Canada, Ireland, the Kingdom of Norway and the People's Democratic Republic of China, and with commercial farmers in eastern Canada and several other countries, were compared with areas identified by the analyses as possessing offshore mariculture potential; and (iii) offshore mariculture potential was examined at several offshore cobia farm locations using locational information communicated by commercial farmers. For the first two kinds of comparisons, good correspondence between established inshore mariculture practice and offshore potential indicates that offshore mariculture could be more easily developed using the existing inshore experience, goods and services, and access to markets. Good correspondence also suggests that favourable conditions for grow-out (water temperature and also food availability for the blue mussel) are likely to be found offshore from existing inshore mariculture installations. The third kind of comparison actually tests predicted potential against the locations of functioning offshore farms. Results from this analysis are described in detail in Chapter 5 of the technical paper.

[8] A sliver polygon is a small remnant polygon resulting from an intersection operation between two or more polygons.

TABLE A1.1

Characteristics and sources of spatial and attribute data used in GIS analyses

Statistics	Resolution	Year	Description	Source
Mean mariculture production (tonnes)	N.A.	2004-2008	Data by country and territory averaged over the period indicated. Hong Kong Special Administrative Region included with China; Channel Islands separated into Guernsey and Jersey.	FAO FishStat Plus; www.fao.org/fishery/statistics/software/fishstat/en
Mariculture intensity (tonnes/km)	N.A.		Mean mariculture production 2004–2008 as a function of coastline length (km).	Derived

Spatial data	Resolution/ scale	Year	Description	Source
VLIZ Maritime Boundaries Geodatabase, Version 5 of 10 October 2009	N.A.	2009	Freely downloadable exclusive economic zones in shapefile format. The database includes two global GIS-layers: one contains polylines that represent the maritime boundaries of the world countries, the other one a polygon layer representing the exclusive economic zone of countries. The database also contains digital information about treaties.	Flanders Marine Institute, Belgium; www.vliz.be/vmdcdata/marbound/index.php
General bathymetric chart of the oceans (GEBCO), GEBCO_08 Grid, 2009	0.9 km		A global 30 arc-second (nominally 0.9 km resolution) grid that is freely downloadable after registration. Software is available to download for viewing and accessing data from the global grid files in ASCII as well as in netCDF format.	British Oceanographic Data Centre; www.bodc.ac.uk/data/online_delivery/gebco/

Spatial data	Resolution/ scale	Year	Description	Source
Current speed (cm/s) Global HYbrid Coordinate Ocean Model (HYCOM) and Navy Coupled Ocean Data Assimilation (NCODA)	8.9 km	2004-2008	The HYCOM/NCODA model-data link was used to make a monthly hindcast of mean monthly current speed and standard deviation from January 2004 to August 2008 at a depth of 30 m and at a resolution of 1/12 degree (nominally about 8.9 km resolution).	The current speed data were processed by HYCOM staff and delivered via the Internet. An overview of the HYCOM evolution and process is provided by Chassignet *et al.* (2009) and also at www.hycom.org
World Port Index	N.A.	2009	The freely downloadable World Port Index contains the location and physical characteristics of and the facilities and services offered by major ports and terminals worldwide (approximately 3 700 entries), in shapefile format.	National Geospatial Intelligence Agency, United States of America; http://msi.nga.mil/NGAPortal/MSI.portal;jsessionid =LknZMdkMlgXnfGhvRGDdLTmSvySYnZJLvR9x1W yvqvxybLJVbrqm!251225267!NONE?_nfpb=true&_ pageLabel=msi_portal_page_62&pubCode=00
Sea surface temperature	4.9 km	1985–2001	Monthly climatology of SST from the National Oceanic and Atmospheric Organization (NOAA), United States of America, from 1985 to 2001 at a nominal 4.9 km resolution.	http://data.nodc.noaa.gov/pathfinder/Version5.0_ Climatologies
Coastal chlorophyll-*a* (CHL2, or Case II)	4.6 km	2003–2009	Monthly mean CHL2 concentration from 2003 to 2009 using a MERIS algorithm at 4.6 km nominal resolution.	Phillipe Garnesson, ACRI-ST, Sophia-Antipolis, France; www.acri-st.fr/English/

Spatial data	Resolution/ scale	Year	Description	Source
2010 World Database on Protected Areas. Annual release – data set number 2C Global data set of marine protected areas	N.A.	2010	All national and international marine protected areas, including national sites not formally declared by government (e.g. proposed). Includes MPA Global 2008 and any other sites that have been identified as having a "marine" component. Data are provided in shapefile format, and GIS capable software is required to view it. Data are freely downloadable after registration.	www.wdpa.org/
Geographic zones	N.A.	2010	Arctic, Northern Temperate, Intertropical, Southern Temperate and Antarctic Zones.	These polygons were generated within this study based on the Tropics of Cancer and Capricorn, and on the Arctic and Antarctic Circles
GADM database of Global Administrative Areas, Version 1	N.A.	2010	GADM is a freely downloadable spatial database of the location of the world's administrative boundaries. The data are available in shapefile, ESRI geodatabase, RData and Google Earth kmz format .	http://gadm.org/home
Coastline length (km)	N.A.	2010	Data by country and territory, derived from GADM (Global Administrative Areas) v. 1.	Calculations made within this study. See Figure A1.11 above that describes the approach in detail

Terminology: N.A. = Not applicable as they are in vector format.

TABLE A1.2
Depth characteristics of experimental and commercial sea cage and longline installations and specifications from manufacturers

Entity	Location	System type	Depth at site (m), or manufacturer's specification	Sources
Sea cages for fish				
Snapperfarm, Inc.	Puerto Rico, United States of America	SeaStation™ offshore submersible	30	O'Hanlon *et al.* (2001)
Cates International	Hawaii, United States of America	SeaStation™ offshore submersible 3000	31	Bybee and Bailey-Brock, (2003), p. 121
Kona Blue Water Farms	Hawaii, United States of America	SeaStation™ offshore submersible 3000	61–67	Kona Blue Water Farms (2003)
University of New Hampshire	New Hampshire, United States of America	SeaStation™ fish cage (SS600)	52	Langan and Horton (2005)
Gulf of Mexico Offshore Aquaculture Constortium	Mississippi, United States of America	SeaStation™ fish cage 600 m3	25	www.masgc.org/oac/Phase%201%20RP1.pdf
Ocean Spar LLC (manufacturer)	Washington, United States of America	SeaStation fully submerged or floating	> 25	www.oceanspar.com/files/OceanSpar_ SeaStation.pdf
Farmocean International (manufacturer)	Sweden	Farmocean 4500	25	www.farmocean.se/General.pdf
SUBflex	Israel	SUBflex single point mooring	40–55 (12 m diameter cage) 0–60 (16 m diameter cage) 50–80 (18 m diameter cage)	SUBflex Open Ocean Net SPM cages; www.subflex.org
Ocean Farm Technologies	Manufacturer's specification	Aquapod A212, A3600, A7000	20–50 - 32–50 - 35–50	Ocean Farm Technologies "Aquapod Site Selection" (www.oceanfarmtech.com) and C. Stock, personal communication (2009)
Workshop on open ocean aquaculture	United States of America	Sea cages with multiple anchors	Comment: Mooring > 100 m a challenge owing to large footprint, capital and maintenance cost of anchoring system	Browdy and Hargreaves (2009)
Asia-Pacific Ocean Research Center, National Sun Yat-sen University	Taiwan Province of China	Gravity cages	30–50 ideal range of water depth for net-cage implementation in the open sea	Huang, C.C., Tang, H.J. and Liu, J.Y. (2008)

TABLE A1.3A
Current speed in mariculture practice for sea cages and longlines

Current speed (cm/s)	Comment	Cage type	Source
60	Not to exceed	General comment to avoid deformation	Beveridge (1996)
103–129	Not to exceed	Farm Ocean 4500	www.farmocean.se/General.pdf
100	90% of cage volume is retained	Ocean Spar SeaStation	Scott and Muir (2006); http://ressources.ciheam.org/om/pdf/b30/00600651.pdf
150–170	"Anti-current" offshore	DFC type	Chen *et al.* (2007) in Cage Aquaculture (Table 4, p. 59); www.fao.org/docrep/010/a1290e/a1290e00.htm
100–120	"Anti-current" semi-open location	PDW type	
50–100	"Anti-current" semi-open location	HDPE type	
150	"Anti-current"	HDPE type submerged	www.alibaba.com/catalog/11644670/Submerged_Style_HDPE_Deep_Water_Sea_Cage.html
72	Maximum for a 144–625 m^3 cage	LMS type	Hunter,Telfer and Ross (2006), Table 3.1 p. 14; www.aqua.stir.ac.uk/public/GISAP/pdfs/SARF003_Full.pdf
82	Maximum for a 700–800 m^3 cage	C-250 type	
93	Maximum for a 3 000–17 000 m^3 type	C-315 type	
10–75	Range given for three cage models	Ocean Farm Technologies Aquapod A212, A3600 and A7000	Ocean Farm Technologies "Aquapod Site Selection" dated 6/5/09 (www.oceanfarmtech.com) and e-mail dated 24 June 2009 from Chris Stock in Outlook Folder Marne GIS
100	Currents that exceed 100 cm/s not generally recommended	Sea cages in general	James and Slaski (2007) (in PNA)

TABLE A1.3B
Current speed in mariculture practice for finfish and mussels

Current speed cm/s	Comment	Species	Source
> 10	To assure sufficient water quality within a cage, currents should remain above 10 cm/s for a major part of the tidal cycle.	Salmon	Tlusty, Pepper and Anderson (2005) citing Puls and Sunderman (1990).
1–9, 1–7, 1–22, 1–10, 1–45 5–10, 2–6	Observations at five inshore sea sites and two lake farming sites taken during two visits, from 5 to 8 hours (five sites) up to three days (two locations) at depths of from 22 to 75 m with recorder 1–2 m from the bottom.	Atlantic salmon	Soto et al. (2003)
3–18 (average)	Twenty salmon farms, Bay of Fundy, Canada, with 24-hour deployments corresponding to two tidal cycles.	Atlantic salmon	Peterson et al. (2001); http://publications.gc.ca/collections/collection_2012/mpo-dfo/Fs97-6-2337-eng.pdf
42 (maximum)	Twenty salmon farms, Bay of Fundy, Canada, with 24-hour deployments corresponding to two tidal cycles.	Atlantic salmon	Peterson et al. (2001); http://publications.gc.ca/collections/collection_2012/mpo-dfo/Fs97-6-2337-eng.pdf
> 100	"Sites where current speeds exceed 100 cm/s for extended periods may not be suitable for growing salmon".	Atlantic salmon	Chang, Page and Hill (2005); www.gnb.ca/0027/Aqu/pdfs/BarryDFO2585.pdf
10–110	"Estimated range of no less than 10 cm/s for several hours and no more than 110 cm/s for more than 24 hours".	Relates to Atlantic salmon and blue mussel among other species considered	Macleod (2007) citing Massachusetts Bay Environmental Forecast System Model, UMass Boston. (M. Jiang, personal communication, 2007); http://envstudies.brown.edu/theses/archive20062007/merriellemacleod_thesis.pdf
10–60	"…sites considered optimal for fish farming in pens have current ranges from 10 to 60 cm/s but varies within this range depending on size and species of fish, stocking density and cage design and configuration".	Relates to "marine or salmonid fish"	Rensell et al. (2007), p. 115; www.fra.affrc.go.jp/bulletin/bull/bull19/13.pdf
< 154	Current speeds are to 3 knots (i.e. 154 cm/s) (offshore site).	Cobia	Aqualider: www.aqualider.com.br (out of business late 2010)
13–77 (range)		Cobia	Snapperfarm, Inc., Puerto Rico, United States of America; Benetti et al. (2010)
< 26	Current is variable but mainly north to south with peaks of 26 cm/s and days of slack current.	Cobia; Double ring olarcirkel, 40, 60 and 100 m circumference	Marine Farms Belize; www.marinefarmsbelize.com
13–129	Current 0.25 knot (13 cm/s) average, max 2.5 knots (129 cm/s).	Cobia; SeaStation 6400, Aquapod 7000 and 100 m Aqualine	Open Blue Sea Farms, Panama; www.openblueseafarms.com
10–50	Siting study for Snapperfarm; mean is 10 and max is 50 observed.	Cobia	Rensell, Kiefer and O'Brien (2006); www.lib.noaa.gov/retiredsites/docaqua/reports_noaaresearch/cobia_aquamodel_final_report.pdf

Current speed cm/s	Comment	Species	Source
< 50	Mainly traditional cobia cages, but some offshore cages at 11 locations.	Cobia	Guangdong and Hainan provinces, China. (C. Zhu, personal communication, 2011)
55	Offshore waters of Penghu Islands, Taiwan Province of China.	Cobia	Miao et al. (2009)
9	Offshore waters of Pingtung County, Taiwan Province of China.		
70–104	Highest speeds encountered as ocean-gyre currents.	*Serioala rivoliana*; Ocean Spar SeaStation cages installed at Keahole Point, Hawaii, (United States of America) 1.6 km offshore	Loverich (2010)
31–103	SeaStation 3000 and 5400, 4.5 km offshore, Jeju province, Republic of Korea.	Parrotfish (*Oplegnathus fasciatus*)	Lim and Lee (no date); www.yslme.org/doc/rmc/Presentation/HanKyu%20lm.pdf
129	Design specification.	Gilthead bream (*Sparus aurata*); SUBflex single-point mooring	12 km offshore in 65 m (R. Tishler, personal communication, 2011).
51–77	Constant speed experienced.	51–77	Constant speed experienced.
103	Maximum experienced.	103	Maximum experienced.
5–50	• "Class I Production up to 20 000 pounds per year (9 072 kg per year). • Minimum depth of 35 feet (10.6 m) for a current velocity of 5 cm/sec (0.1 knots) to a minimum depth of 20 feet (6.1 m) for current velocities of 40 cm/sec (0.8 knots) or greater Class II Production between 20 000 to 100 000 pounds per year (9 072 to 45 360 kg per year). • Minimum depth of 45 feet (13.7 m) for a current velocity of 5 cm/sec (.01 knots) to a minimum depth of 25 feet (7.6 m) for current velocities of 50 cm/sec (1.0 knots) or greater Class III Production over 100 000 pounds per year (45 360 kg per year). • Minimum depth of 60 feet (18.2 m) for a current velocity of 5 cm/sec (0.1 knots) to a minimum depth of 40 feet (12.1) for current velocities of 50 cm/sec (1.0 knots) or greater.	Finfish	Langenburg and Sturges (1999), Table 2. There is an appendix with a chart relating current speed, production and depth from which the data on the left have been derived. These estimates are from the point of view of environmental protection rather than from maximizing production, it seems.
> 50	SeaStation SS600 and SS3000 cages 10 km offshore of New Hampshire, United States of America, with current speed "often exceeding 50 cm/s".	Atlantic halibut, Atlantic haddock, Atlantic cod	Fredricksson et al. (2003)
10–50	Optimal with lesser speeds affecting fillet quality and greater speeds resulting in a rapid increase of the feed conversion ratio with cultivation becoming financially unattractive.	Gilthead bream	Ferreira, Saurel and Ferreira (2012)

Current speed cm/s	Comment	Species	Source
N/A	"At a current speed of 15 cm/sec, the water at a site is exchanged about 100 times per day. An exchange rate of 2–3 times is typically needed to keep the levels of nutrients in the water column lower than the critical load."	N/A	Grøttum and Beveridge (2007), citing Olsen, Slagstad and Vadstein (2005) p. 148.
5–20 good; < 1 and > 50 poor		Not named	Halide (2008) Appendix 1 (appears to be modelling for unnamed fish species in tropical waters); http://data.aims.gov.au/cads/CADS_TOOL_Technical_Guide.pdf
< 5	Very weak current, poor mass flux and inconsistent current direction. Depletion likely at the centre of farms. Only suitable for low-density farming or spat holding.	*Perna canaliculus* and *Mytilus galloprovincialis*	Inglis, Hayden and Ross (2000), Box table, p. 21
5–10	Weak current velocities of generally widely varying direction leading to some depletion at centre of farm.	*Perna canaliculus* and *Mytilus galloprovincialis*	Inglis, Hayden and Ross (2000), Box table, p. 21
10–20	Moderate-low depletion that may be more marked at downstream end of farm. Depletion is more likely to be observed in centre of farmed area.	*Perna canaliculus* and *Mytilus galloprovincialis*	Inglis, Hayden and Ross (2000), Box table, p. 21
> 20	Strong current flow. Little depletion but cumulative effect of many ropes longlines in the direction of flow could result in (remainder of text is missing from the original article).	*Perna canaliculus* and *Mytilus galloprovincialis*	Inglis, Hayden and Ross (2000), Box table, p. 21
15–20	Bottom culture (moderate grow-out densities).	*Mytilus edulis*	Newell (2001)
5	Longlines, if given adequate spacing.	*Mytilus edulis*	Newell (2001)
10–15	Rafts in order to prevent depletion.	*Mytilus edulis*	Newell (2001)
10–30	Offshore longline.	*Mytilus edulis*	R. Langan, personal communication, 2009
< 10; infrequently up to 50	Hawke Bay, North Island, New Zealand.	Bivalve shellfish, including greenshell mussels, *Perna canaliculus*	Cheney et al. (2010)
< 15–30	Opotiki, North Island, New Zealand.	Bivalve shellfish, including greenshell mussels, *Perna canaliculus*	Cheney et al. (2010)

TABLE A1.4A

Temperatures for grow-out of cobia

Temperature or range	Comment	Location	Source
< 22 No growth		Viet Nam	Nhu *et al.* (2009)
< 18 Stop eating		Viet Nam	Nhu *et al.* (2009)
15 Mass mortality	Five weeks in 2008.	Viet Nam	Nhu *et al.* (2009)
22–30 Mean monthly range		Viet Nam	Nhu *et al.* (2009)
<16 Severe stress, mortalities		United States of America	M. Osterling, personal communication, 2011
16–32; > 20 preferred	Conditions in the wild.	Not stated	Kaiser and Holt (2005)
> 26 Optimal growth	Culture conditions.	Not stated	Kaiser and Holt (2005)
21–22	Feeding activity reduced.	Taiwan Province of China	Miao *et al.* (2009)
19	Feeding ceases.	Taiwan Province of China	Miao *et al.* (2009)
< 16 and > 36	May result in mass mortality.	Taiwan Province of China	Miao *et al.* (2009)
22–32	Optimal temperature range.	Not specified	Miao *et al.*, 2009, citing Chang et al., 1999
25–27 mean spring to autumn; 21–22 mean winter < 16 low temperature		Penghu Archipelago, Taiwan Province of China	Shih, Chou and Chiau (2009)
27–29 Ambient conditions		Snapperfarm, Isla Culebra, United States of America	Rensel, Kiefer and O'Brien, 2006
< 16 High mortality		Penghu Archipelago, Taiwan Province of China	Liao et al. (2004)
23.5–28 year round		Sea cage areas in southern Taiwan Province of China	Liao et al. (2004)
28–32 Highest growth rates; < 20 growth rates decreased	Fish fed to satiation.	Penghu Archipelago, Province of China	Ueng et al. (2001)
26 and above	On growing.	Not stated	Kaiser and Holt (2007); www.fao.org/fishery/culturedspecies/Rachycentron_canadum/en
27–28 year round	On growing.	Open Blue Sea Farms, Panama	B. O'Hanlon, personal Communication, 2011
25–32	On growing.	Snapperfarm, Inc., Puerto Rico, United States of America	Benetti et al. (2010)

TABLE A1.4B

Temperatures for grow-out of Atlantic salmon

Temperature or range	Comment	Location	Source
6–16	Grow best in sites with these temperature extremes.	Generalized	FAO (2011); www.fao.org/fishery/culturedspecies/Salmo_salar/en
0.6–15.6	Winter and summer temperatures not to be exceeded for any length of time.	Maine, United States of America	University of Maine; www.umaine.edu/mainesci/Archives/MarineSciences/salmon-farming.htm
8–18	Optimal range for culture.	Tasmania, Australia	Anon, (2002); www.pir.sa.gov.au/__data/assets/pdf_file/0010/33895/salmon_fs.pdf
12–16	Best growth.	Tasmania, Australia	Anon, (2002); www.pir.sa.gov.au/__data/assets/pdf_file/0010/33895/salmon_fs.pdf
0–21	Tolerate this range.	Tasmania, Australia	Anon, (2002); www.pir.sa.gov.au/__data/assets/pdf_file/0010/33895/salmon_fs.pdf
6–16	Grow-out range.	N/A	Verspoor et al. (2007)
12–16	Preferred range.	Gippsland, Victoria, Australia	Gippsland Aquaculture Industry Network Inc. (2011); http://growfish.com.au/Grow/Pages/Species/Trout.htm
> 22	Not recommended for farming if exceeded on a regular basis.	Gippsland, Victoria, Australia	Gippsland Aquaculture Industry Network Inc. (2011); http://growfish.com.au/Grow/Pages/Species/Trout.htm
0.7	Lowest temperature for survival.	Bay d'Espoir, Newfoundland, Canada	Anon. (2009); www.dfo-mpo.gc.ca/science/enviro/aquaculture/acrdp-pcrda/fsheet-ftechnique/pdf/02-eng.pdf
0–15	This range, along with strong currents and high tides, provide ideal conditions.	Maine, United States of America	Maine Aquaculture Innovation Center (2011); www.maineaquaculture.org/industry/species.html#salmon
0.5–15.2	Measurements from 20 farms over two years.	Bay of Fundy, Canada	Peterson et al. (2001); http://publications.gc.ca/collections/collection_2012/mpo-dfo/Fs97-6-2337-eng.pdf

TABLE A1.4C

Temperatures for grow-out of blue mussel

Temperature or range °C	Note	Location	Source
-1.08–15.6	Range at two commercial farming sites, with two stations per site.	Notre Dame Bay, St. John's, Newfoundland, Canada	Khan, Parrish and Shahidi (2006)
5.5–16.3	Range at shellfish farm.	West Scotland, United Kingdom	Karayucel and Karayucel (1999)
10–18	Range at commercial and experimental sites with improved growth or condition and where food supplies and/or nutrients were adequate (not limited to blue mussel).	Worldwide review	Saxby (2002)
16–22	Exhibit maximum growth in this range.	South Australia	Anon. (2000); www.pir.sa.gov.au/__data/assets/pdf_file/0005/33899/mussels_fs.pdf
4.4–21.1	Range for culture.	Maine, United States of America	Island Institute (1999). The Maine guide to raft culture
4.4–10	Ideal for culture.	Maine, United States of America	Island Institute (1999). The Maine guide to raft culture
18.3	Begin to lose byssal strength.	Maine, United States of America	Island Institute (1999). The Maine guide to raft culture
21.1	Begin to suffer mortality.		
15.8	Optimal temperature for growth (model result).	Prince Edward Island, Canada	Lauzon-Guay, et al. (2006); www.int-res.com/articles/meps2006/323/m323p171.pdf
< 20	Prevent summer mortality.	Eastern North America	Newell (2001)
5–20	Well acclimated for this range.	Worldwide review	Goulletquer, P. (2009); www.fao.org/fishery/culturedspecies/Mytilus_edulis/en
0.30–15.03	Winter and summer daily means.	Lunenburg, Nova Scotia, Canada	Hatcher, Grant. and Schofield (1997)
-2–25	Often exposed to temperatures in this range.	Atlantic Canada	New Brunswick Professional Shellfish Growers Association (2011); www.acpnb.com/statistics.cfm
> 5	Required for somatic and germinal growth.	Eastern North America	Newell and Moran (1989)
5–16	Range affecting growth along with salinity, food quantity and quality.	10 km offshore near Portsmouth, New Hampshire, United States of America	Langan and Horton (2003)

TABLE A1.4D

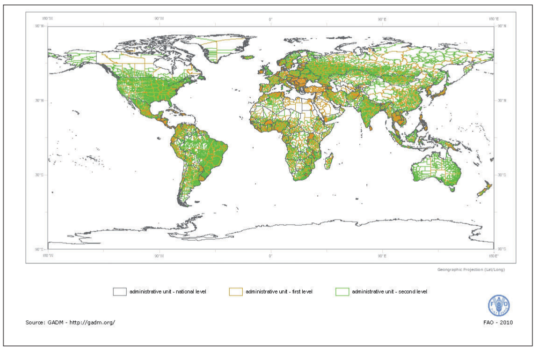
Chlorophyll-concentrations in relation to grow-out of blue mussel

Chlorophyll-*a* concentration mg/m^3	Note	Location	Source
Mean 1–10	Concentrations predominant at sites where bivalves did not appear to be greatly limited by lack of nutrients.	Global review	Saxby (2002)
> 1	Significant growth of Perna canaliculus occurred only when above this concentration.	Marlborough Sounds, New Zealand	Hawkins *et al.* (1999)
< 1 Very poor to poor	Growth of Perna canaliculus in embayments as generic guidelines.	New Zealand	Inglis, Hayden and Ross (2000)
1–2 Moderate	Growth of Perna canaliculus in embayments as generic guidelines.	New Zealand	Inglis, Hayden and Ross (2000)
2–4 Good	Growth of Perna canaliculus in embayments as generic guidelines.	New Zealand	Inglis, Hayden and Ross (2000)
4–8 Ideal	Growth of Perna canaliculus in embayments as generic guidelines.	New Zealand	Inglis, Hayden and Ross (2000)
> 8 Little known	Growth of Perna canaliculus in embayments as generic guidelines.	New Zealand	Inglis, Hayden and Ross (2000)
> 1	Mussel shell growth becomes faster with temperatures 7–8 °C.	Loch Kishorn, Scotland	Karayucel & Karayucel (1999)
< 1– 5	Offshore experimental site with good results for growth and grow-out.	Near Isles of Shoals, New Hampshire, United States of America	Langan and Horton (2005)

4. Global data sets for estimates of offshore mariculture

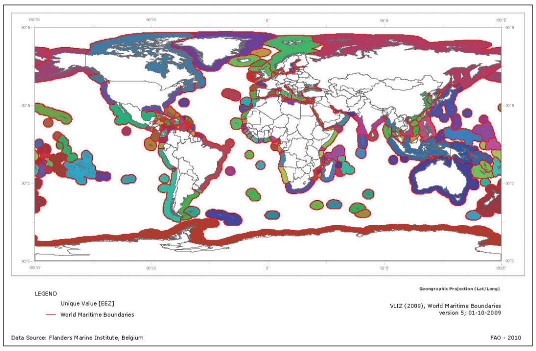
Boundaries of sovereign nations

GADM database of global administrative areas



http://www.gadm.org/

Exclusive economic zones of the world - version 5



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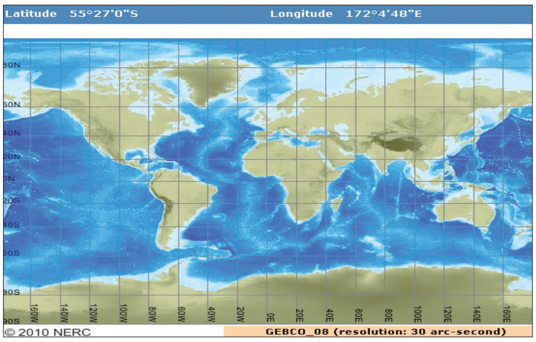
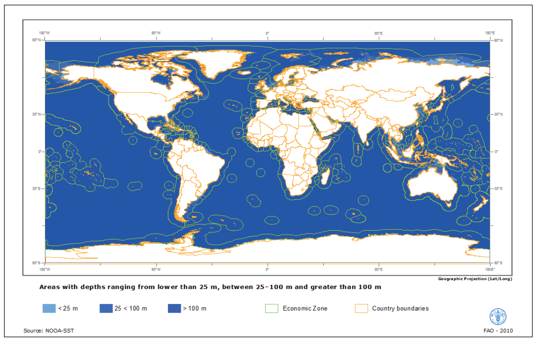
Depth and current speed as the fundamental criteria characterizing the technical limits of present offshore submerged cage and longline culture systems

General bathymetric chart of the Oceans



http://www.gebco.net/

Regions with depths ranging from lower than 25 m, between 25–100 m and greater than 100 m



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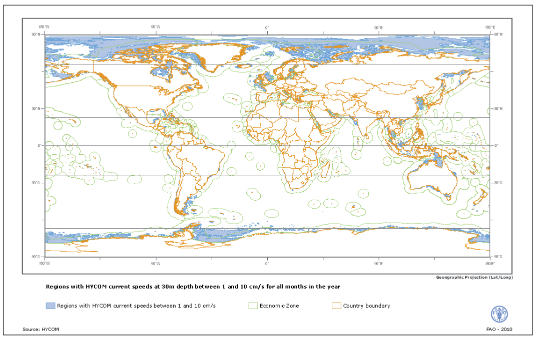
Regions with HYCOM current speeds at 30 m depth between 1 and 10 cm/s for all months in the year



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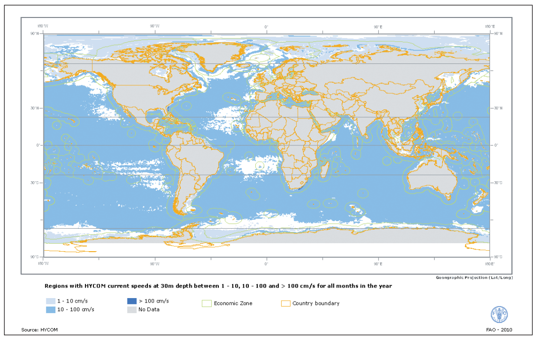
Regions with HYCOM current speeds at 30m depth between 1–10, 10–100 and > 100 cm/s for all months in the year



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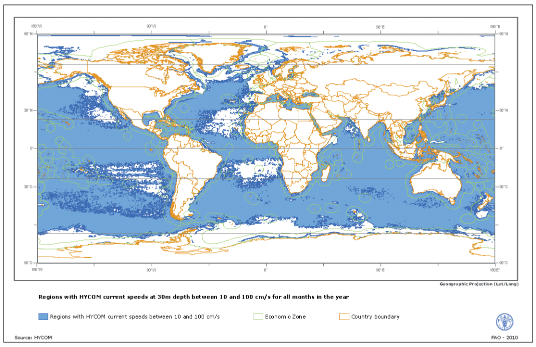
Regions with HYCOM current speeds at 30m depth between 10 and 100 cm/s for all months in the year



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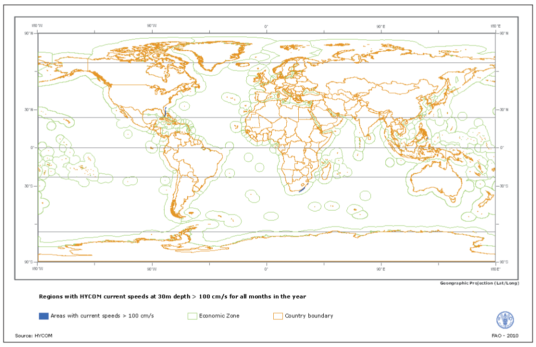
Regions with HYCOM current speeds at 30m depth > 100 cm/s for all months in the year



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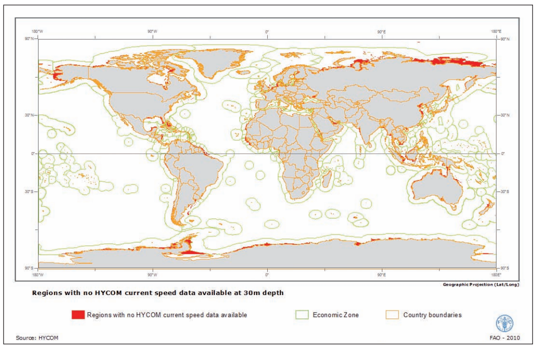
Regions with no HYCOM current speed data available 30m depth



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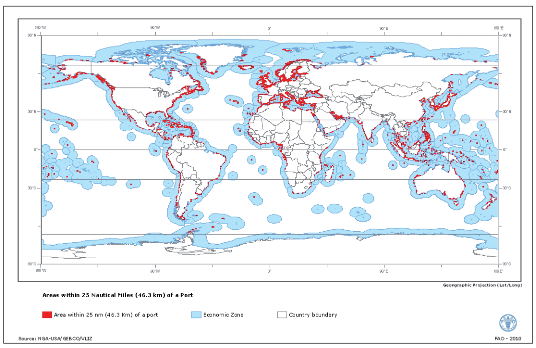
Note: Areas with no current speed data are those with depths less than 30m (i.e. all of the areas close to the shorelines) so they are difficult to see on a world map).

Distance offshore from onshore infrastructure related to economic cost limits on transportation and on reliable access from a port to the sea

Areas within 25 nautical miles (46.3 km) of a port



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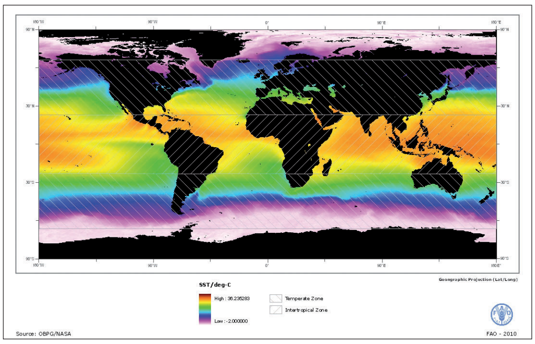
Favourable offshore grow-out environment based on temperature requirements of representative fish and mussels and on food availability measured as chlorophyll concentration for the latter

Aqua MODIS climatology sea surface temperature (Spring 2002–2009)



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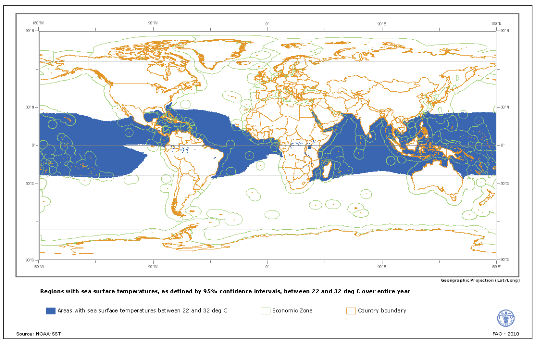
Regions with sea surface temperatures, as defined by 95% confidence intervals, between 22 and 32° C over entire year for Cobia



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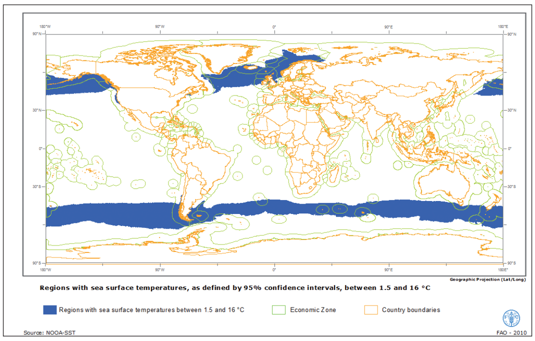
Regions with sea surface temperatures, as defined by 95% confidence intervals, between 1.5 and 16°C over entire year for Atlantic salmon



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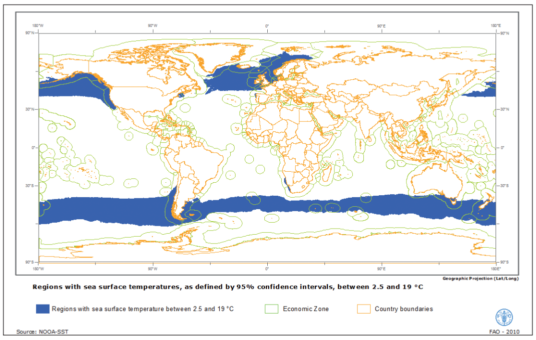
Regions with sea surface temperatures, as defined by 95% confidence intervals, between 2.5 and 19°C over entire year for blue mussel



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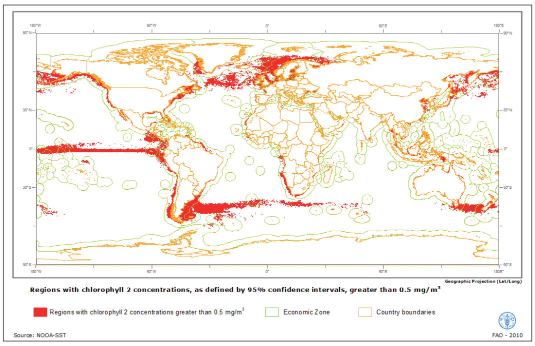
Regions with chlorophyll 2 concentrations, as defined by 95% confidence intervals, greater than 0.5 mg/m3 that were combined for the months available in each hemisphere for the blue mussel



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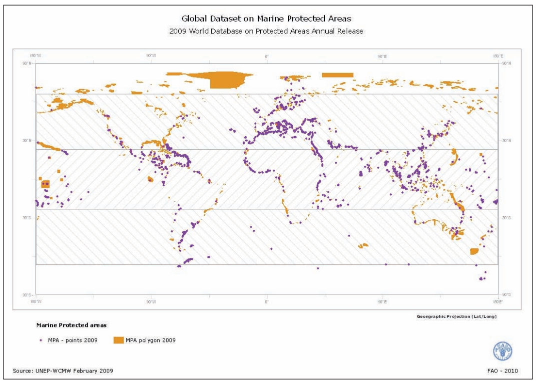
Competing, conflicting and complementary uses of ocean space

2009 World database on protected areas



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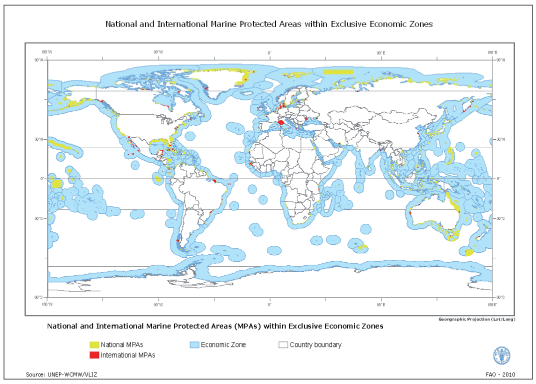
National and international marine protected areas within exclusive economic zones



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