Annex 3

Remote sensing for the sustainable development of offshore mariculture

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ABSTRACT

Aquaculture is practised worldwide in highly variable environments. Many of the environmental factors that influence the sustainable development of aquaculture can be measured by remote sensing. Over recent decades, satellite remote sensing has supported the systematic, routine measurement of the seas, oceans, inland waters, and atmosphere. Recent advances in remote sensing systems, communications technology and computer processing mean that remote sensing products are more accessible and that these products will prove useful for offshore mariculture applications.

Information about the safety of aquaculture structures can be provided from processed satellite radar altimetry and coastal high-frequency radar. Several important information requirements related to a healthy environment for the growth and well-being of cultured organisms can also be met through remote sensing, including sea surface temperature, primary productivity and turbidity. However, some applications demand higher spatial resolution image products, or more frequent delivery than those operationally provided by different national and international agencies or organizations. For some products, cloud cover can limit the frequency of data acquisition.

There are three main applications of remote sensing for offshore aquaculture: (i) global and regional "suitability assessment" can integrate remote sensing data for analysis within geographic information systems (GIS) with data sets such as bathymetry, accessibility (distance to ports), and political and management information; (ii) "site selection and zoning" requires higher spatial resolution imagery products and several freely available data sets that can support activities that include chlorophyll-*a* concentration, turbidity and sea surface temperature. Currents, waves and winds are highly variable, and access to data requires engaging with commercial suppliers of satellite-derived data or a regional agency managing coastal high-frequency radar; and (iii) "monitoring" applications for offshore mariculture usually demand frequent observations and information reports on the environmental status (e.g. currents or chlorophyll-*a* concentration).

Remote sensing plays an important role in planning and management activities,

as does monitoring. The unique capability of satellite remote sensing to provide regular, repeated observations of the entire globe or specific regions at different spatial scales will also become increasingly important in the context of global climate change and the ecosystem approach to aquaculture.

With the proliferation of the technology, the range of satellite remote sensing data and information products available can be overwhelming. Many potential users of remote sensing data lack access to training, support, and tools to acquire and use data sets to support their activities. This review provides guidance to acquire data and begin to process data for incorporation into further analysis using GIS. The review points potential users to software and support available, and provides some demonstration remote sensing products and case studies at global and regional levels of relevance to offshore mariculture.

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Abbreviations and acronyms

AATSR	Advanced Along-Track Scanning Radiometer
ACRI-ST	Observation de la Terre-Environnement (R&D company, France)
API	application programming interface
ASAR	Advanced Synthetic Aperture Radar
ATSR	Along-Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
AVISO	Archiving, Validation and Interpretation of Satellite Oceanographic data
CAP	Chile Aquaculture Project
CCRS	Canada Centre for Remote Sensing
CHL	chlorophyll
CNES	Centre national d'études spatiales (French Space Agency)
CZCS	Coastal Zone Color Scanner
DO	dissolved oxygen
EAA	Ecosystem approach to aquaculture
EEZ	exclusive economic zone
EOS	Earth Observing System (NASA)
ERS	Earth Resources Satellite
ESA	European Space Agency
ESRI	Environmental Systems Research Institute
FAO	Food and Agriculture Organization of the United Nations
GEOSAT	Geodetic Satellite
GHRSST	Group for High-Resolution Sea Surface Temperature
GIS	geographic information systems
GOES	Geostationary Orbiting Earth Satellites
HAB	harmful algal bloom
HDF	Hierarchical Data Format
HF	high-frequency (radar)
HYCOM	HYbrid Coordinate Ocean Model
IOCCG	International Ocean Colour Coordinating Group
KML	Keyhole Markup Language (for Google Earth or Maps)
MERIS	Medium Resolution Imaging Spectrometer
MESH	Mapping European Seabed Habitats
MGET	Marine Geospatial Ecology Tools
MODIS	Moderate Resolution Imaging Spectroradiometer
MPA	marine protected areas
m/s	metres per second
NASA	National Aeronautics and Space Administration
NASO	National Aquaculture Sector Overview
NEST	Next ESA SAR Toolbox
netCDF	Network Common Data Form
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NRT	near real-time
SAR	synthetic aperture radar
SeaWiFS	Sea-viewing Wide Field-of-View Sensor

SMOS	Soil Moisture and Ocean Salinity satellite
SST	sea surface temperature
SWH	significant wave height
TIROS	Television Infrared Observation Satellite
TSM	total suspended matter
WCS	Web Coverage Service
WFS	Web Feature Service
WMS	Web Map Service

1. Introduction

1.1 Objectives and overview

Aquaculture is practised worldwide in highly variable environments. Many of the environmental factors that influence the sustainable development of aquaculture can be measured by remote sensing. As such, remote sensing provides several essential elements to support the implementation of the ecosystem approach to aquaculture (EAA).11 The planning and implementation of the EAA requires explicit consideration of spatial information about ecosystem components and properties, and recent advances in remote sensing have greatly enhanced our ability to describe and understand natural resources, facilitate planning of aquaculture development, and support environmental impact assessments and monitoring. Satellites enable a unique synoptic view of the seas and oceans and regular repeated observations of the entire globe and specific regions. Satellite earth observation systems provide a range of observation data that complement and extend data available from in situ oceanographic sensors (e.g. buoys and ships). Operational oceanography data and information products of relevance to offshore mariculture, derived wholly or partly from remote sensing, include sea surface temperature (SST), primary productivity, ocean winds, currents12, salinity and wave heights.

The build-up of long time-series of data and advances in data processing mean that series of daily, weekly, monthly, annual and seasonal data are now available for many products, which are known as "climatologies". Ocean productivity and temperature data provided from remote sensing are important for the development of coupled atmosphere-ocean global circulation models. These data sets have made a large contribution to the scientific understanding of the Earth's ocean-climate system for climate change research and the prediction of its impacts. The relationship between climate change and ocean primary production is likely to be a key determinant of fish and fisheries production (Cushing, 1982; Forget, Stuart and Platt, 2009). In the realm of mariculture, climate change will affect where development can take place.

Advances in information and communications technology mean that potential users have timely and open access to these global and regional oceanographic data and information products. However, the range of satellite remote sensing data and information products available is sometimes overwhelming, especially to a non-remote sensing specialist. The aim of this review is to provide support to potential users who are active in offshore mariculture development on the application of remote sensing.

1.2 Offshore mariculture

The great diversity of coastal waters, including their topography, exposure (hydrodynamic energy) and depths, makes it difficult to define the conditions typical for offshore mariculture, and attempts to do this must be seen as preliminary approaches rather than absolute. As a premise for the further discussion, the Food and Agriculture Organization of the United Nations (FAO) has established general criteria for mariculture activities in three categories: coastal mariculture, off-the-coast

[11] The EAA is a "strategy for the integration of the activity within the wider ecosystem such that it promotes sustainable development, equity and resilience of interlinked social-ecological systems." (FAO, 2010; Aguilar-Manjarrez, Kapetsky and Soto, 2010).

[12] Geostrophic currents can be measured. Unlike surface currents caused by wind and tides, geostrophic current is the horizontal movement of surface water arising from a balance between the pressure gradient force and the Coriolis force (http://oceanmotion.org/html/background/geostrophic-flow.htm).

mariculture and offshore mariculture. These are mainly based according to the distance from the coast and water depth (revealing the degree of exposure), but also according to the operational requirements and accessibility to the farms in rough weather (Table A3.1).

TABLE A3.1
General criteria for coastal, off-the-coast and offshore aquaculture based on some environment and hydrographic characteristics

	Coastal	Off-the-coast	Offshore
Location/ hydrography	• < 500 m from the coast • ≤10 m depth at low tide • Within sight • Usually sheltered	• 500 m–3 km from the coast • 10–50 m depth at low tide • Often within sight • Somewhat sheltered	• > 2 km, generally within continental shelf zones, possibly open ocean • > 50 m depth
Environment	• Hs usually < 1 m • Short period winds • Localized coastal currents, possibly strong tidal streams	• Hs < 3–4 m • Localized coastal currents, some tidal streams	• Hs 5 m or more, regularly 2–3 m • Oceanic swells • Variable wind periods • Possibly less localized current effect
Access	• 100% accessible • Landing possible at all times	• > 90% accessible on at least once daily basis • Landing usually possible	• Usually > 80% accessible • Landing may be possible, periodic, e.g. every 3–10 days
Operation	• Regular, manual involvement, feeding, monitoring, and more	• Some automated operations, e.g. feeding, monitoring, and more	• Remote operations, automated feeding, distance monitoring, system function

Note: Hs = significant wave height – a standard oceanographic term, approximately equal to the average of the highest one-third of the waves.

Source: Lovatelli and Aguilar-Manjarrez (forthcoming).

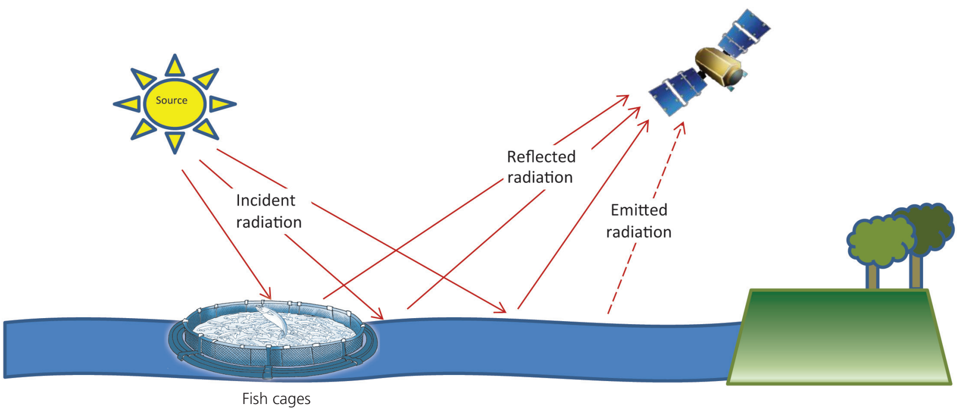
The use of the criteria in Table A3.1 calls for a careful approach because the term "offshore" could be understood differently by different people and because offshore locations according to the above criteria could be in internal waters in some countries with extensive archipelagos and in international waters in other countries.

The criteria can only give a preliminary idea of the farming conditions. Each national situation and prevailing local conditions at the sites should always be considered individually. Another way of defining mariculture locations, not shown in Table A3.1, is "sheltered" for coastal mariculture; "partly exposed" (e.g. > 90° open) for off-the-coast mariculture; and "exposed" (open sea, e.g. > 180° open) for offshore mariculture. For estimating offshore mariculture potential, Kapetsky, Aguilar-Manjarrez and Jenness (this publication) adopted a simplified definition of offshore aquaculture by Drumm (2010). Drumm's (op. cit.) definition calls attention to open sea areas, significant exposure and severe sea conditions. The distance from the shore or safe harbour may or may not be a factor.

1.3 What is remote sensing?

Remote sensing is defined as "the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation" (Lillesand, Kiefer and Chipman, 2007). Remote sensing devices are sensors mounted on satellites and aircrafts, or installed at fixed coastal locations, that can measure the electromagnetic energy that is emitted or reflected by the features of the Earth's surface. Remote sensing data are usually presented as an image comprised of a regular grid of picture elements, or pixels, which can then be displayed on a computer screen using specialized software or common applications such as Google Earth.

FIGURE A3.1
Overview of the process of remote sensing



The process of remote sensing is illustrated in Figure A3.1. The source of energy or illumination is usually the sun, but for radar sensors the radar energy is generated by the radar antenna. The energy source travels through the atmosphere and interacts with the target (e.g. ocean or ground surface). The reflected or emitted radiation is received by the remote sensor and converted into a signal that can be recorded and displayed as either numerical data or as an image.

For a recent and detailed review on remote sensing applications to fisheries and aquaculture, see Dean and Populus (2013). The remote sensing review describes the basics of remote sensing and its main applications to support fisheries and aquaculture management. It provides practical guidance for planning and implementing the use of remote sensing, including data selection and acquisition, image processing and the integration of images, within geographic information systems (GIS), and also includes case studies to illustrate how remote sensing has been applied to support coastal aquaculture mapping and sensitive habitat mapping, monitoring development of potentially harmful ocean conditions, and the identification of potential fishing grounds.

1.4 Main types of remote sensing data

The main types of remote sensing data can be classified into optical imagery and radar:

- **Optical images** – optical sensors (like our eyes) measure electromagnetic radiation in the visible blue, green and red wavelengths as well as infrared wavelengths (that human eyes do not detect). The source of energy for optical remote sensing is the sun, and the sensors measure reflected and emitted solar energy. Optical images can be interpreted intuitively by users; examples of data and information products include ocean chlorophyll-*a* concentration and photo-like images such as fish cages. In cloudy regions, it may not be possible to acquire imagery as often as needed or desired because optical wavelengths do not penetrate through clouds. Thermal imaging is a special case of optical imaging in which the measured energy is emitted by the Earth and is related to the temperature of the emitting surfaces; an example of thermal measurement is SST.
- **Radar** – operate in longer wavelengths (microwaves) and are not affected by cloud cover; radar data, however, are more challenging to interpret than optical imagery. Radar data are usually processed by a specialist or organization into a product that can be more easily used by a fisheries and aquaculture specialist. There are three types of radar that are of interest for offshore mariculture:

- **Imaging radar.** Presented as images, but containing different information compared with optical images, such as the sea surface roughness. Radar images can also provide clear identification of ocean surface structures such as fish cages or shellfish longlines.
- **Radar altimetry.** Complex data processing is conducted to provide information on surface currents, wave heights and wind speed.

- **High-frequency (HF) radar** – requires that radar stations are installed along the coastline in the area to be monitored. HF radar provides estimates of surface current direction and speed, as well as wave heights, within a specific area.

1.5 Key characteristics of remote sensing data

There is unprecedented availability of global and regional oceanographic data and information products. Many of the data and information products come from satellite remote sensing. The number and variety of products is huge, with products presenting numerous parameters with different temporal and spatial resolutions. In order to select available products, the user needs to consider the following:

- **Parameter** – defines what is being measured by the satellite sensor and/or derived using models, complementary in situ data, or other remote sensing data. The accuracy and precision of the measurements are obviously important.
- **Spatial extent** – remote sensing can be applied at a range of scales, such as global, regional and local areas.
- **Spatial resolution** – there are technical definitions of spatial resolution, but, as remote sensing data are usually processed into an image format, it is sufficient to understand that spatial resolution is the size of the individual pixel recorded by the sensor. Depending on the application, "low resolution" might be 20 m and "high resolution" might be 0.5 m (e.g. aquaculture structure mapping), or "low resolution" may be 50 km and "high resolution" might be 1 km (e.g. chlorophyll-*a* concentration). Users often desire high-resolution satellite data, but for large areas compromise is often needed because data may be too expensive to acquire and data volumes impractical to process. The spatial resolution of the product has an important impact on whether the product can describe geographic variability or patterns in enough detail (and at the desired time steps at a given level of resolution) for the intended application. For example, an available regional surface currents data set may be too coarse to describe local surface currents that are influenced by tides, which are of interest to a farm manager.
- **Revisit frequency** – defines the frequency of observations that can be made of the same area, which for satellite remote sensing depends on the satellite orbit and the extent and spatial resolution of the system. Data and information acquired for global studies are typically less detailed (relatively coarse) compared with those acquired for specific areas; however, they can be acquired more frequently. Cloud cover also affects the revisit potential of optical systems. While many sensors claim frequent revisit, their capacity to cover large areas may be limited. Some satellite sensors can "look" to the side of their orbit to provide more frequent coverage, but in most cases vertical observations are better for accurate, detailed mapping. Constellations of two or more of the same or compatible satellites can improve the revisit frequency.
- **Time series** – the time period over which consistent observations are available, usually referring to the historical period. Future continuity of data supply from a particular sensor, or a group of sensors with similar properties, may be important to ensure that frequent, ongoing information will be available to support the user's information needs.

- **Timeliness –** the speed that a product is made available to a user. Near real-time (NRT) products are designed to be delivered as quickly as possible (www.eurogoos.org), and are often called "nowcast" by oceanographers. Historical time series ("hindcast" or "offline") products can be developed over long periods and are delivered only after careful compilation and calibration. It is also possible for remote sensing data to be incorporated into models to forecast ocean conditions. The timeliness of a product may also depend on the amount of processing required.
- **Product or data level –** a common challenge for a non-remote sensing specialist is that most data suppliers also refer to available "data levels", which describe the amount of processing that the data supplier has conducted before the product is made available to the user. The simplest approach for non-specialists is to start with the higher level data (i.e. Level 3) because they are most likely to be products that can be directly integrated within a GIS and used for analysis. Data levels can be summarized as follows:
  - Level 1A: unprocessed instrument data at full resolution.
  - Level 1B: instrument calibrations have been applied to Level 1A data to provide more consistent values.
  - Level 2: derived variables at the same resolution as the source Level 1 data, e.g. SST data, where the spatial resolution of the data may vary across the image.
  - Level 3: derived variables in a regular grid formation, e.g. a regular grid of SST data. Level 3 data are sometimes called "binned" because they have a regular grid, or "mapped" if they have been map projected.

2. Data and information requirements

2.1 General requirements

There are several potential user groups of oceanographic remote sensing, and their data requirements differ partly based on the extent of their mandate or interest. From a global perspective, organizations such as FAO are exploring the use of GIS and remote sensing for estimating the potential for offshore mariculture in order to encourage countries with large absolute or relative potentials to undertake national-level studies, to improve the definition of that potential as a step towards updating policy on offshore mariculture, and to improve planning for aquaculture development. At a national or regional level, fisheries and aquaculture regulators and marine spatial planners also represent a potential user group, with data needed to support management of competing uses of the marine environment in a management zone or exclusive economic zone (EEZ). At a local level (and sometimes regional level), aquaculture developers and operators are interested in selecting the most suitable sites for aquaculture operations and in monitoring the environment.

Based on these broad groups of users and the spatial extent and resolution of their data and information requirements, there are three main potential applications of remote sensing for offshore mariculture:

- **Global and regional suitability assessment** – to contribute biophysical information to a process to determine the broad areas with potential for the culture of different species and their associated culture systems.
- **Zoning and local site selection** – to define marine zones and local areas that are appropriate for offshore mariculture development, within areas considered broadly suitable for different species and culture systems.
- **Monitoring** – to monitor the marine environment of operational farms, including local conditions and the marine zone, that may influence cultured species.

Data and information requirements can also be presented thematically, focusing on parameters of interest to users. Thematic requirements are broadly similar for fish, shellfish and marine plant aquaculture, but some parameters are more or less important for different cultured species. The subsections below provide more detail on the above potential applications and thematic data and information requirements.

2.2 Global and regional suitability assessment requirements

Much of the data required for spatially detailed and comprehensive analyses for zoning and siting of offshore mariculture is available only at national and subnational levels. Collection, compilation and spatial analysis of national and subnational data sets to estimate offshore mariculture potential at global and regional levels would be time consuming and expensive. However, there are spatial data sets useful for global and regional assessments of aquaculture potential. These data sets have two characteristics. The first characteristic is that the resolution is coarse, ranging from 1 km for marine bathymetry and up to 2 degrees for significant wave height. Estimations of mariculture potential are based on long-term data sets. Thus, the second characteristic is that the time-variable data must be organized into climatologies to enable analyses. Climatologies are compilations of time-variable data collected at relatively short time intervals with the observations organized into time steps that range from daily to monthly and annual compilations. Climatologies describe the short-term observations in terms of means, standard deviations and sample size for each time step. The longer the duration of the climatology, the better the coverage of seasonal and interannual variability.

Assessments of mariculture potential at global and regional levels focus on the most fundamental requirements for mariculture development. Basically, at global and regional levels, assessments of mariculture potential consider environments suitable for the culture systems (e.g. depths and current speeds for sea cages), environments that favour grow-out of cultured organisms (e.g. water temperature, food availability as chlorophyll-*a* for filter feeders), cost-distance from onshore support to offshore culture installations, and competing, conflicting and complementary uses of marine space (e.g. marine protected areas, navigation lanes).

Site suitability assessments require long-term data sets (historical data) that will provide a description of past environmental conditions and time series showing trends and changes (EuroGOOS; www.eurogoos.org). These data and their sources are described in the following sections.

2.3 Zoning and site selection requirements

Zoning and aquaculture site selection is the process of identifying and characterizing the most promising locations for offshore aquaculture.

The process may begin by considering a large area (potentially the whole EEZ), and systematically narrowing down the options into zones on the basis of different parameters, and ending finally to a smaller area for a detailed "siting study". The zoning and site selection process requires a range of different data and information, including socio-economic, political, legal and planning data, and may be part of a broad marine spatial planning process (Ehler and Douvere, 2007), or it may be focused on regional spatial planning for fisheries and aquaculture (FAO/Regional Commission for Fisheries, 2011).

Zoning and site selection requires data that are relatively detailed and that have more frequent observations compared with a suitability assessment. Historical data are required, which can be inputs for analysis and ecological modelling and model verification. Ireland provides an example of national zoning and site selection for offshore aquaculture development. The "offshore aquaculture development in Ireland" study (Watson and Drumm, 2007) implemented a process to survey all of Ireland's potential sites, which were narrowed down based on analysis of water depth, shelter, and proximity to landing facilities.

2.4 Monitoring requirements

Monitoring existing farms or marine areas typically needs NRT data, which may be compared with baselines from long-term averages. NRT data must provide the "most usefully accurate description of the present state of the sea, including living resources" (EuroGOOS, 2011; www.eurogoos.org). NRT delivery typically means a user has access to data and information products within a few hours to 24 hours. Based on integrated data within models, forecasts may provide predictions of the future condition of the sea and the air masses just above it. An important area for remote sensing monitoring is the mapping and prediction of potentially harmful algal blooms (HABs).

HAB (also called a red tide) may cause harm through the production of toxins or by their accumulated biomass, which can affect co-occurring organisms and alter food-web dynamics. Impacts include human illness and mortality following the consumption of, or indirect exposure, to HAB toxins, substantial economic losses to coastal communities and commercial fisheries, and HAB-associated fish, bird and mammal mortalities. "To the human eye, blooms can appear greenish, brown, and even reddish-orange depending upon the algal species, the aquatic ecosystem, and the concentration of the organisms" (www.whoi.edu/redtide).

An exception to the NRT monitoring is the monitoring and inventory of aquaculture structures, which would typically be required on an annual basis by the regulator of the industry.

2.5 Thematic data requirements

For each of the application areas described above, it is useful to categorize data and information requirements according to the parameters that impact fish, shellfish and marine plant cultivation: (i) environments where it is technically feasible and economically advantageous to place offshore culture installations and onshore support facilities; and (ii) environments that promote fast growth and high survival rates of cultured organisms.

Requirements can include long-term averages and variability, as well as NRT delivery of data and information and forecasts of future conditions.

2.5.1 Physical parameters for siting culture systems

- **Currents** – in this context, the reference is to ocean surface currents that are wind or tidal driven. Suitability assessment and site selection for offshore mariculture needs long-term historical information on the strength and variability of currents because currents disperse aquaculture wastes and possibly lessen the prevalence of certain ectoparasite infections; however, currents that are too strong can impact the safety of the installation and the cost of marine transport and access and servicing of the facilities, as well as the cultured organisms themselves (e.g. energy expended on swimming rather than growth).
- **Wind** – in this context, average wind speed. Suitability assessment and site selection for offshore mariculture may benefit from long-term information on the exposure of an area to strong winds and storms given the impact on wave heights and currents. There is also a direct wind effect on service boat operations apart from wave height. Monitoring for warnings and forecasts regarding the expected track and severity of storms may also be useful.
- **Wave height** – is technically defined as the difference in elevation between the crest of an ocean wave and the neighbouring trough; significant wave height (SWH) is a commonly used measure and is the average height of the one-third largest waves. Suitability assessment and site selection for marine aquaculture needs long-term information on SWH because of its importance for cost-effective and robust engineering of the marine aquaculture structures.

Table A3.2 Provides a summary of technical data and information needs for offshore mariculture.

TABLE A3.2

Environmental parameters where it is technically feasible and economically advantageous to place offshore culture installations and onshore support facilities

	Zoning (hindcast) and site selection		Monitoring (near real-time and forecast)
	Global/regional scale	Local scale	
Currents	Fish, shellfish and plants: • Multi-year averages and seasonal variability • 4 km resolution	Fish, shellfish and plants: • Multi-year averages and seasonal variability • 500 m resolution	Fish, shellfish and plants: • Hourly measurements • 7-day forecasts • 500 m resolution
Winds	Fish, shellfish and plants: • Multi-year averages and seasonal variability • 4 km resolution	Fish, shellfish and plants: • Multi-year averages and seasonal variability • 1 km resolution	Fish, shellfish and plants: • Hourly measurements • 7-day forecasts • 1 km resolution
Wave heights	Fish, shellfish and plants: • Multi-year averages and seasonal variability • 4 km resolution	Fish, shellfish and plants: • Multi-year averages and seasonal variability • 1 km resolution	Fish, shellfish and plants: • 7-day forecasts • 1 km resolution

2.5.2 Environmental parameters that promote fast growth and high survival rates of cultured organisms

- **Temperature** – sea surface temperature (SST) is physically determined by the incidence of solar radiation, ocean circulation and the depth of the mixed layer, which is affected by upwelling, surface winds and bathymetry. Offshore mariculture requires data and information on sea temperatures because fish and shellfish growth rates (and survival) are affected by average temperature and temperature variability. SST is the temperature of the water close to the surface, or the ocean "skin", and SST data are most likely applicable for suitability assessment and monitoring, the latter because models of ocean productivity need temperature data.
- **Primary production** – is the production of organic compounds from carbon dioxide through the process of photosynthesis, primarily by microscopic algae. Net primary production accounts for losses to processes such as cellular respiration. Primary production is mostly determined by the availability of light and mineral nutrients, the latter being affected by stratification and mixing of the water column. Offshore mariculture requires data and information on the primary production of an area because shellfish are filter feeders that rely on sufficient concentration of food particles such as phytoplankton for their growth. Chlorophyll-*a* concentration products that remote sensing can support are suitability assessment, zoning and site selection, and monitoring. Fish farmers may be interested in historical data and monitoring extremes of primary production, which may be harmful to fish health through oxygen depletion or which produce toxic compounds.
- **Turbidity** – is a measure of the transparency of sea water. Turbidity can be affected by local and regional currents and waves, coastal erosion, bottom type, phytoplankton concentration and river plumes. Offshore mariculture requires data and information on turbidity of an area because high concentrations of inorganic suspended matter can negatively affect fish and shellfish growth and health. The primary interest would be historical data.
- **Salinity** – is a measure of dissolved salt content, and variations can result from rainfall, evaporation, river discharge and ice formation. Offshore mariculture needs to understand the variable levels of salinity because feeding, growth and survival of shellfish can be affected by low salinity. Freshwater river plume distribution is an important site section issue and the interest is in historical data.
- **Dissolved oxygen (DO)** – a relative measure of the amount of oxygen that is dissolved or carried in a given medium. Marine aquaculture needs to understand the typical levels of DO and the presence of "dead zones" (i.e. hypoxic [low oxygen] areas in the world's oceans) because hypoxia may have detrimental effects on fish oxygen consumption, physiology, feed intake, growth and well-being.

Table A3.3 provides a summary of the environmental data information needs for offshore mariculture.

TABLE A3.3

Environmental parameters that promote fast growth and high survival rates of cultured organisms

	Site suitability, zoning (hindcast) and site selection		Monitoring (near real-time)
	Global/regional scale	**Local scale**	
Temperature	Fish, shellfish and plants: • Multi-year averages and seasonal variability • 4 km resolution	Fish, shellfish and plants: • Local variability can be important based on species selection • 1 km resolution	Fish and shellfish: • Daily to hourly measurement to support modelling of primary production • 1 to 4 km resolution
Primary production*	Fish and shellfish: • Frequency of extremes (HABs) Shellfish: • Multi-year averages and seasonal variability • 4 km resolution	Fish and shellfish: • Frequency of extremes (HABs) Shellfish; • Multi-year averages and seasonal variability; • 1 km resolution	Fish and shellfish: • 7-day forecasts of extremes (HABs) Shellfish: • Daily to hourly measurements • In situ and 1 km resolution
Turbidity	Fish, shellfish and plants: • Multi-year averages and seasonal variability • 4 km resolution	Fish, shellfish and plants: • Multi-year averages and seasonal variability • 1 km resolution	Fish and shellfish: • Daily measurement • 1 km resolution
Dissolved oxygen**	Fish, shellfish and plants: • Frequency of DO extremes (HABs) • In situ only	Fish, shellfish and plants: • Frequency of DO extremes (HABs) • In situ only	Fish and shellfish: • Daily measurement of DO • In situ only
Salinity	Fish, shellfish and plants: • Multi-year averages and seasonal variability. • Identify freshwater river plumes • 4 km resolution	Fish, shellfish and plants: • Multi-year averages and seasonal variability • Identify freshwater river plumes • 1 km resolution	Fish, shellfish and plants: • Not important

Note: *Including phytoplankton species analysis. ** Depth profiles of parameters are ideally required.

3. Available remote sensing data products

The subsections below aim to provide a summary of the available remote sensing data products that are able to meet the thematic data and information needs described in the previous section.

3.1 Environmental parameters to place offshore culture installations and onshore support facilities

To establish if an area represents a safe environment for offshore mariculture requires information on surface currents, wave heights and winds. Satellite radar altimeter systems are capable of measuring sea surface height, from which ocean circulation patterns and sea level are determined on a global scale. Marine weather forecasts, which include wave height predictions, are based partly on satellite remote sensing and can be used for the installation and management of offshore mariculture. Altimetry data are also used to compute wave heights (e.g. SWH measured in metres) and wind velocity (metres per second [m/s]).

There has been an almost continuous series of radar altimetry missions since 1985, starting with GEOSAT, and measurements are currently continuing with JASON-1 (2001), Ocean Surface Topography Mission on JASON-2 (2008), and with Envisat (2002). Table A3.4 provides a summary of radar altimetry missions, and Table A3.5 lists the main sources of radar altimetry-based products.

TABLE A3.4
Summary of radar altimetry satellite missions

Satellite(s)	Operational period	Orbit
GEOSAT GEOSAT Follow-On	1985–1990 1998–2008	17-day repeat cycle
ERS-1 ERS-2 Envisat	1992–1996 1995–2011 2002 to present	35-day repeat cycle
Topex/Poseidon Jason-1 Jason-2	2001–2005 2001 to present 2008 to present	10-day repeat cycle

Source: http://earth.eo.esa.int/brat/html/missions/welcome_en.html

Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO) distributes free satellite altimetry data from Topex/Poseidon, Jason-1, ERS-1 and ERS-2, and Envisat in NRT on a daily basis. AVISO products include a 25-km spatial resolution “geostrophic current” product and a 90-km spatial resolution SWH and surface wind product. Satellite altimetry does not measure tidal currents, which are a result of the rise and fall of the water level due to tides. The effects of tidal currents on the movement of water in and out of bays and offshore can be substantial and more important than geostrophic currents for aquaculture development. To determine tidal currents requires oceanographic modelling, and it is not a product that can be delivered from remote sensing. The free AVISO data are delivered as NRT daily data and there are no long-term averages provided. The coarse resolution of the products may mean that they are only useful for global and regional suitability assessments for offshore mariculture. The AVISO SWH and wind data at 90-km resolution are used in this review in Chapter 5 “Demonstration products and case studies”.

The European Space Agency (ESA), with support from the French Space Agency (Centre national d'études spatiales), has established the GlobWave Project to provide satellite wave products to users around the globe. The project is ongoing and provides free access to satellite wave data and products in a common format, both historical and in NRT.

TABLE A3.5

Sources of radar altimetry products

Portal Name	Details	Access
AVISO	Geostrophic currents, SWH and surface winds.	www.aviso.oceanobs.com/en/data/products
GlobWave	Satellite wave data products (under development).	www.globwave.org
MyOcean	Provides access to a range of regional and global ocean data, including AVISO products.	www.myocean.eu.org
eoPortal	ASAR and ERS and others. Searchable online catalogue, particularly useful for searching ESA archives.	http://catalogues.eoportal.org
Ocean Watch	NASA, NOAA, AVISO surface currents and many other data. Preview and download various data, including for custom user specified regions.	http://las.pfeg.noaa.gov/oceanWatch

Coastal HF radar is another source for surface currents and wave height data, which provides higher spatial resolution data (e.g. 1 km) and on a more frequent and timely basis (e.g. real-time hourly data).

Of course, availability of HF radar data requires investment in radar stations along the coastline of interest. HF radar now cover increasingly large areas of the United States of America; for example, through the National Oceanic and Atmospheric Administration (NOAA) HF Radar National Server and Architecture Project (http://hfradar.ndbc.noaa.gov), which provides a demonstration of the HF radar display capability using Google Maps.

HF radar operates at long wavelengths (6 to 30 m) and requires two or more radars to be looking at the same area of water using two or more different viewing angles (www.codar.com/intro_hf_radar.shtml).

The complex radar processing allows precise information of the surface currents and wave heights. While providing timely data on the latest ocean currents and wave conditions, HF radar data are not archived to develop long-term climatologies.

A potential alternative source of currents data that is more suitable for offshore mariculture is the HYbrid Coordinate Ocean Model (HYCOM; www.hycom.org). The HYCOM consortium is a partnership of institutions that represent a broad spectrum of the oceanographic community, and it aims to meet a number of objectives, including the three-dimensional depiction of the ocean state at fine resolution in real-time and the provision of boundary conditions for coastal and regional models.

Data from HYCOM can be accessed by establishing an agreement with the consortium; its currents data may be more useful than freely available altimetry for global and regional suitability assessment and zoning and site selection.

A disadvantage is the need for processing of the available data into the appropriate depths and time steps that may be beyond desktop capabilities.

Another option for currents data is from MERCATOR-OCEAN (www.mercator-ocean.fr). The MERCATOR-OCEAN "observed ocean" system is based on altimetry and in situ data measurements. The satellite data sources include altimetry satellites and SST. In situ data are measurements taken at sea, including submerged sensors and drifting buoys fitted with a satellite positioning system. The spatial resolution of the global observed currents products and forecasts is 1/4 degree (~20 km).

3.2 Environments that promote fast growth and high survival rates of cultured organisms

To establish if an area represents a healthy environment for the growth and well-being of cultured organisms for offshore mariculture requires information on temperature, primary production, turbidity, salinity and DO. The importance of these different parameters varies according to the cultured species (fish, shellfish or plants).
Remote sensing can provide operational oceanographic data on SST, primary production, turbidity and, more recently, salinity at very coarse spatial scales. Information on DO cannot be provided from remote sensing.

3.2.1 Sea surface temperature

A summary of satellites and sensors relevant for SST observations is provided in Table A3.6. Since the late 1970s, SST measurements have been operationally available from the Advanced Very High Resolution Radiometer (AVHRR) sensors on the NOAA/TIROS meteorological satellites.

Other sensors include: the National Aeronautics and Space Administration's (NASA) Moderate Resolution Imaging Spectroradiometer (MODIS) sensors onboard the Earth Observing System AQUA and TERRA satellites; ATSR and AATSR from ESA missions; and NOAA's Geostationary Orbiting Earth Satellites (GOES) satellites that are geostationary over the Western Hemisphere.

TABLE A3.6
Summary of sea surface temperature-related optical remote sensing systems

Sensor	Satellite(s)	Operational period	Orbit/coverage	More Information
AVRR	NOAA 4 to 19 and TIROS METOP-A	1978 to present; 2007 to present	Polar orbit; 2 800 km swath; global coverage every day	www.oso.noaa.gov/poesstatus
MODIS	EOS TERRA EOS AQUA	1999 to present; 2002 to present	Polar orbit; 2 330 km swath; global coverage every one to two days	http://modis.gsfc.nasa.gov
Imager, Sounder	GOES 1 to 12	1975 to present	Geostationary; orbit Western Hemisphere	http://goes.gsfc.nasa.gov/
ATSR AATSR	ERS-1 and 2 Envisat	1991 to present; 2002 to present	500 km swath; global coverage every 3 days	http://envisat.esa.int/instruments/aatsr http://envisat.esa.int/handbooks/aatsr

Table A3.7 provides an overview of popular sources of SST data. The Group for High-Resolution Sea Surface Temperature (GHRSST: www.ghrsst.org) provides operational access to nearly all satellite SST data sets in a common format and within several hours of acquisition by the satellite instrument. GHRSST products (typically 10 to 50 km spatial resolution) are generated by combining complementary satellite and in situ observations. Several high spatial resolution (< 5 km resolution) regional SST analysis products are available; for example, from ESA for the Mediterranean (Medspiration project; http://projets.ifremer.fr/cersat/Information/Projects/MEDSPIRATION2).

Complementary to GHRSST, SST data products are also provided by national agencies that operate SST-related missions. The "4 km AVHRR Pathfinder Project" has produced a 4 km global coverage product using the AVHRR sensor series for the entire 1985–2001 time series. The 4 km AVHRR Pathfinder Project data are used in this review in Chapter 5 "Demonstration products and case studies".

TABLE A3.7

Sources of sea surface temperature data and information products

Source	Details	Access
NOAA	4 km AVHRR Pathfinder Project; 4 km global product provides long-term SST "climatologies", including mean, variance and anomalies.	www.nodc.noaa.gov/satellitedata/pathfinder4km
NASA	Aqua MODIS Seasonal Climatology Sea Surface Temperature.	http://oceancolor.gsfc.nasa.gov/cgi/l3
GHRSST	Level 4 gridded SST products (typically 10 to 50 km spatial resolution).	www.ghrsst.org
Rutgers University	AVHRR; real-time and archive SST daily composite for eastern United States of America, including the Gulf of Mexico.	http://marine.rutgers.edu/mrs/sat_data
MyOcean	Provides access to a range of regional and global SST data, including GHRSST.	www.myocean.eu.org

Note: Data levels are described in Section 1.5.

3.2.2 Primary production and turbidity

Ocean colour satellite sensors cover a specific range in the electromagnetic spectrum and can provide users with several derived parameters including chlorophyll-*a* concentration and turbidity (total suspended matter [TSM]). Chlorophyll-*a* concentration (mg/L) provides an estimate of the amount of chlorophyll-*a*-like pigments in the upper few centimetres of the water column and is related to primary production. TSM is a measure of turbidity and represents concentrations of suspended particulate matter (mg/L).

The optical properties of ocean waters have been used to define Case 1 and Case 2 waters (Mobley et al., 2004; Morel, 1988): Case 1 waters are those waters whose optical properties are determined primarily by phytoplankton and related coloured dissolved organic matter and detritus degradation products. Case 2 waters are everything else, namely waters whose optical properties are significantly influenced by other constituents such as mineral particles, coloured dissolved organic matter, or microbubbles, whose concentrations do not co-vary with the phytoplankton concentration. The distinction between Case 1 waters (usually coastal) and Case 2 waters (usually offshore) is important for application of algorithms used to process satellite remote sensing data.

A summary of satellites and sensors related to ocean colour observations is provided in Table A3.8. No single ocean colour sensor is capable of observing every part of the globe every day, so a combination of sensors is often used. Following the successful launch in 1978 of the Coastal Zone Color Scanner (CZCS), there have been several overlapping ocean colour satellite missions. Currently, SeaWiFS, MODIS, MERIS and others provide data to support operational oceanography products. There are also national missions such as Oceansat-1 (the Republic of India). The International Ocean Colour Coordinating Group (IOCCG) provides a good summary of the current and future availability of ocean colour sensors (www.ioccg.org/sensors_ioccg.html). Future sensors of particular interest are those onboard ESA's Sentinel 3 (launch 2013) and NOAA's NPP and NPOESS (2011 and 2014).

TABLE A3.8

Summary of ocean colour-related optical remote sensing systems

Sensor	Satellite(s)	Operational period	Orbit/coverage
SeaWiFS	OrbView-2	1997 to present	Polar orbit; 1 500 km swath
MODIS	EOS TERRA EOS AQUA	1999 to present 2002 to present	Polar orbit; 2 330 km swath; global coverage every one to two days
MERIS	Envisat	2002 to present	Polar orbit; 1 200 km swath
Ocean Colour Monitor (OCM) 1 and 2	Oceansat-1 and 2	1999 to present 2009 to present	1 400 km swath; global coverage every one to two days

Source: IOCCG (2009).

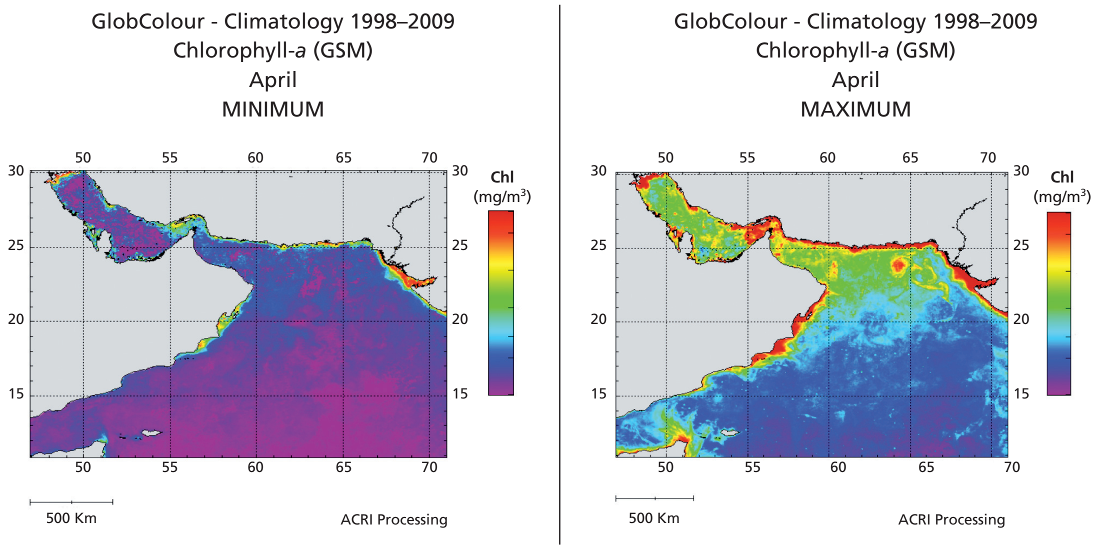
Table A3.9 provides an overview of popular sources of ocean colour data. The "ESA GlobColour" project has merged observations made with different satellite systems to enable global daily coverage. GlobColour provides time series from 1997 to the present of consistently calibrated and validated global ocean colour information with a 4.6 km spatial resolution coverage.

The ACRI-ST InfoceanDesk environment monitoring service has recently made available global and regional climatology products of chlorophyll-*a* concentration and TSM at 4.6 km and 1 km resolution. These climatology products are derived from EU FP7 and ESA MyOcean GlobColour Products, ESA ENVISAT MERIS data, NASA MODIS, and SeaWiFS data. Demonstration products include:

- Monthly average chlorophyll concentration (1998–2009);
- Maximum and minimum average monthly chlorophyll concentration (1998–2009);
- Monthly anomaly of average chlorophyll concentration (1998–2009). The anomaly is the relative difference of the data for a particular month with the average of all observations available during the months of the 1998–2009 period.

These products were added to FAO GeoNetwork: www.fao.org/geonetwork/ (simply search for "Chlorophyll Climatology"). An example product for the Gulf of Oman area is shown in Figure A3.2.

FIGURE A 3.2
Minimum and maximum and chlorophyll concentration in the Gulf of Oman area for the month of April for the period 1998 to 2009



Source: ACRI-st Infocean Desk.

The processing of more than a decade of historical satellite data to produce chlorophyll concentration climatology products provides valuable data for the aquaculture site selection process for new facilities. Analysis of the frequency and distribution of algal bloomww events may support spatial and temporal risk assessment. In Chapter 5, a pilot web-based harmful algal bloom warning system for the Chilean aquaculture sector is described, which used MERIS and MODIS remote sensing data; was an important demonstration that contributed to the establishment of the ACRI-ST InfoceanDesk.

TABLE A3.9

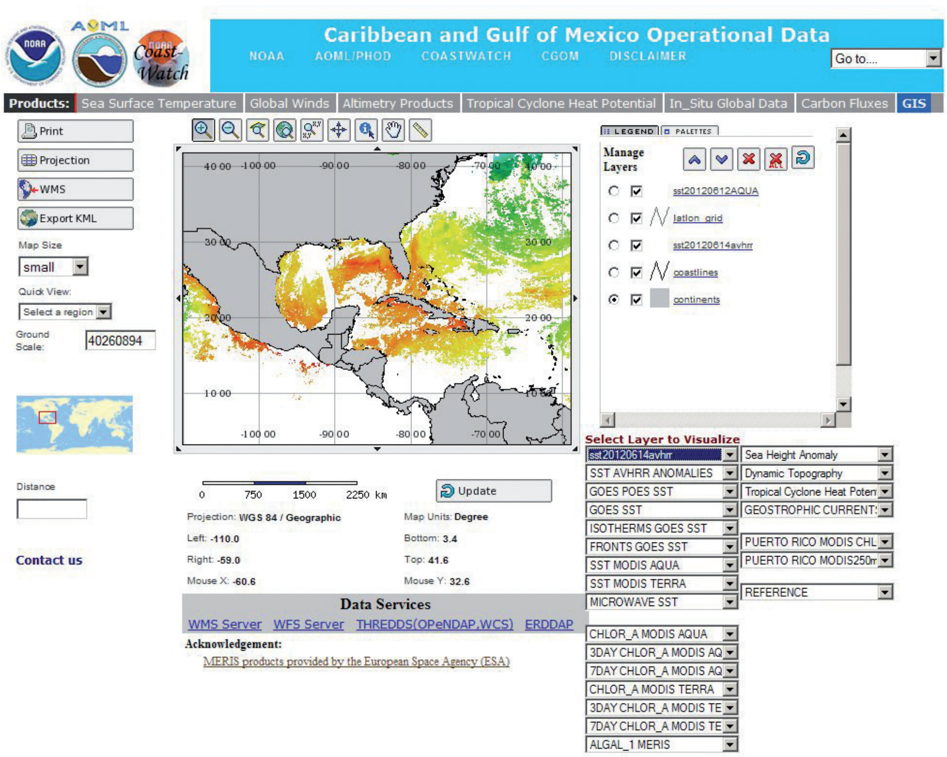
Sources of ocean colour data and information products

Source	Details	Access
InfoceanDesk	Merging of MERIS, SeaWiFS and MODIS Level 2 data; daily, weekly and monthly Level 3 products (15-day delay or daily NRT). Extraction of ocean colour data for user-defined areas is possible and a free GlobColour subscription service allows users to systematically obtain NRT products at 1 km spatial resolution of a specific area. The ACRI-ST InfoceanDesk environment monitoring service is known as "Pôle Mer" in France, and is partly funded by FUI and PACA region.	http://hermes.acri.fr
NASA Ocean Color Web	CZCS, SeaWiFS, and MODIS Level 1 to 3 data; daily, weekly, monthly and seasonal climatologies.	http://oceancolor.gsfc.nasa.gov
NOAA Coastwatch	Provides access to multiple satellite ocean remote sensing data and products for selected marine zones of the United States of America.	http://coastwatch.noaa.gov
MyOcean	MyOcean provides access to a range of information services. As part of MyOcean, the ACRI-ST Global Ocean Colour Processing Unit provides access to a range of regional and global ocean colour data, including GlobColour.	www.myocean.eu.org

Note: Data levels are described in Section 1.5.

The "NASA Ocean Color Web" provides access to CZCS, SeaWiFS and MODIS data in product levels from 1 to 3, including daily, weekly, monthly and seasonal climatologies. Other regional ocean colour services exist, including NOAA Coastwatch (see Figure A3.3).

FIGURE A3.3
NOAA Coastwatch Caribbean and Gulf of Mexico Web GIS of operational oceanographic data



Source: NOAA (2000), http://cwcgom.aoml.noaa.gov/cgom/webgis.phtml

3.2.3 Salinity

Passive satellite radar can detect the low levels of emitted microwave radiation from the Earth's surface.

Launched in 2011, the joint Argentine Republic and the United States of America Aquarius satellite will provide monthly maps of global changes in ocean surface salinity with a resolution of 150 km, showing how salinity changes from month to month, season to season, and year to year at a global scale. (www.nasa.gov/mission_pages/aquarius/news/aquarius20110922.html).

In 2010, ESA launched the Soil Moisture and Ocean Salinity (SMOS) satellite, which carries the Microwave Imaging Radiometer with Aperture Synthesis (MIRAS) passive microwave instrument (www.esa.int/esaLP/ESAL3B2VMOC_LPsmos_0.html).
It had one objective: to provide salinity measurements. SMOS data are intended to be used for global climate change research and have a coarse spatial resolution of 40 km; however, the salinity measurements are expected to be averaged over areas of 200 × 200 km (ESA, 2009), and so they will not likely be useful for offshore mariculture applications. More information on SMOS is provided at the European Space Agency[13].

3.3 Competing and conflicting uses

Remote sensing may also support the identification of locations that will conflict with other uses, and identify areas where there may be advantages of possible complementary uses of adjacent space. As described by Kapetksy, Aguilar-Manjarrez and Jenness (this review), uses for offshore mariculture currently under discussion include marine protected areas (MPAs), wind-farm supporting structures, wave energy, and unused oil or gas platforms, which can all be detected and monitored by remote sensing.

MPAs would reduce the areas having potential for offshore mariculture; remote sensing has the potential to provide environmental indicators such as long-term average primary productivity and ocean temperatures that are relevant to the design of MPAs. Remote sensing may also help to exclude some other areas that are the most productive fishing grounds, or sensitive habitats, that may not be within an MPA (e.g. seagrass beds – see Section 5.5).

3.4 Summary

Satellite remote sensing has the potential to meet the data and information needs of a range of different applications for offshore mariculture, including global and regional suitability assessment, zoning and site selection, and monitoring.

Several thematic offshore mariculture data requirements can be addressed and Table A3.10 summarizes the recommended freely available data along with the temporal and spatial resolution. It is clear that the freely available remote sensing data have some limitations for aquaculture applications because of their spatial resolution, particularly the radar altimetry derived SWH and wind data. However, these products provide an excellent low-cost entry into the application of remote sensing for aquaculture applications in order to gain experience and understand the potential. After users conduct an initial study, they can contact the suppliers and establish the costs for customized regional data at higher spatial resolution.

[13] SMOS scientific objectives: www.esa.int/esaLP/ESAS7C2VMOC_LPsmos_0.html.

TABLE A3.10

Recommended freely available remote sensing data products

Parameter	Spatial resolution	Temporal resolution	Recommended source
Chlorophyll-*a* (mg/L)	1 km regional 4.6 km global	Daily NRT Offline/hindcast Climatology	ACRI-ST InfoceanDesk environment monitoring service
TSM (mg/L)	1 km regional 4.6 km global	Daily NRT Offline/hindcast Climatology	ACRI-ST InfoceanDesk environment monitoring service
SST (°C)	4 km global	Offline/hindcast Climatology	4 km AVHRR Pathfinder Project
	10–50 km global	Daily NRT	GHRSST
SWH (m)	90 km global	Daily NRT	AVISO
Winds (m/s)	90 km global	Daily NRT	AVISO
Currents (m/s)	25 km global	Daily NRT	AVISO
	1/12 degree (~8 km)	Offline/hindcast model	HYCOM consortium
	1/4 degree (~20 km)	NRT and forecast	MERCATOR-OCEAN

Note: TSM = total suspended matter; SST = sea surface temperature; SWH = significant wave height; NRT = near real-time.

Currently available chlorophyll-*a* concentration and SST data are suitable for offshore mariculture applications in terms of spatial resolution at a global scale. In coastal environments, 4 km and 1 km spatial resolution products may be affected by the reflectance from the land surface, especially if the coastline is characterized by many small islands and narrow inlets. The temporal resolution of products can be limited because of cloud cover and satellite orbit characteristics. The combination of multiple ocean colour sensors by the GlobColour project and ACRI-ST InfoceanDesk environment monitoring service is beneficial, and some monitoring applications such as algal blooms and seston depletion could be operational in the near future.

4. Tools and resources

Users may now be ready to explore remote sensing data for a particular application based on the information provided in the previous chapters. The sections that follow introduce resources (information sources, references, tools) for further information and technical support for remote sensing application for offshore mariculture.

4.1 Getting Started

It can be difficult to know how or where to begin using remote sensing data for offshore mariculture. Before starting, it is important to define what information or outcome is expected. To scope out what is available and what is possible, the following steps are recommended:

1. Define the ecosystem boundaries of a study area.
2. Identify the relevant issue(s) to address (e.g. suitability assessments, zoning and site selection, and/or monitoring).
3. Define the spatial scale (e.g. farm, watershed, region) and the temporal scales (i.e. time scales are relevant in addressing aquaculture strategies and planning).
4. Compare the data and information requirements with the FAO information resources and other information resources (see Sections 4.2 and 4.3).
5. Use different satellite imagery catalogues to determine if images are available for an area for free download or purchase, depending on the sensor (see Section 4.4). Choose from the different data formats (see Section 4.5), and consider the costs of data (see Section 4.6).
6. Select an appropriate software application, starting with the free or open source options (see Section 4.7). Some of the tools require more time and effort to learn. An application like Google Earth can be useful to gain an understanding of the geographic setting of an area.
7. Investigate if there are local or regional organizations with expertise in using remote sensing for marine applications, such as a university or government agency, to provide assistance.

4.2 FAO information resources

The FAO Fisheries and Aquaculture Resources Use and Conservation Division actively promotes the use of GIS, remote sensing and mapping for the analysis of fisheries and aquaculture data, and supports the development of sustainable fisheries and aquaculture. Two key sources of information of direct relevance to remote sensing are: (i) the GIS portal (GISFish); and (ii) the new National Aquaculture Sector Overview (NASO) maps collection Web site to inventory and monitor aquaculture.

GISFish (www.fao.org/fishery/gisfish/index.jsp). GISFish is a site from which to obtain the global experience on GIS, remote sensing and mapping as applied to fisheries and aquaculture. GISFish sets out the issues in fisheries and aquaculture, and demonstrates the benefits of using GIS, remote sensing and mapping to resolve them. The global experience provided by GISFish is captured in "Issues, Publications, Activities, Training, Data and Tools, Contacts, Discussions, News and Events". Using the "Data and Tools" menu of GISFish, access is gained to a wide range of fisheries and aquaculture associated data, including links to remote sensing data and tools. The FAO Aquaculture Service has produced a series of fisheries technical publications on GIS since the early 1980s, which are readily available in GISFish. Among these publications, the technical papers by Meaden and Kapetsky (1991)[14] and Meaden and Do Chi (1996) stand out, from a practical viewpoint, as the most consulted GIS-related publications for fisheries and aquaculture from FAO to date.

A single technical manual for both sectors is currently in preparation to update the previous work, given that fisheries and aquaculture share a number of common spatial planning issues (e.g. data, models, training, experience) that require synergies that need to be strengthened for the future implementation of the ecosystem approach to aquaculture/ecosystem approach to fisheries and marine spatial planning approaches (Meaden and Aguilar-Manjarrez, 2013).

NASO maps (www.fao.org/fishery/naso-maps/en). An excellent starting point for a spatial inventory of aquaculture with attributes that include species, culture systems and production is the FAO NASO map collection. The collection consists of Google maps showing the location of aquaculture sites and their characteristics at an administrative level (state, province, district, etc.) and, in some cases, even at an individual farm level. The data presented depend on the degree of aquaculture development and the resources available for data collection and the level of clearance provided by each country. The information provided in NASO has been primarily provided by experts on aquaculture and by national authorities and supplemented by data collected/processed by FAO to illustrate reported production statistics.

The NASO maps Web site also illustrates a few "select aquaculture sites" (www.fao.org/fishery/naso-maps/selected-aquaculture-sites/jp). The sites have been selected by national experts and aim to illustrate: (i) a few examples of different culture systems, cultured species, environments (freshwater, brackish water and marine) and scales (local, waterbody and/or watershed); and (ii) the potential of remote sensing for operational management of aquaculture. In addition to the NASO maps Web site, Figure A3.4 illustrates some examples of imagery found in Google Earth of relevance to offshore mariculture, which are also available in the NASO map collection.

[14] Chapter 4 of Meaden and Kapetsky (1991) includes a chapter on remote sensing as a data source.

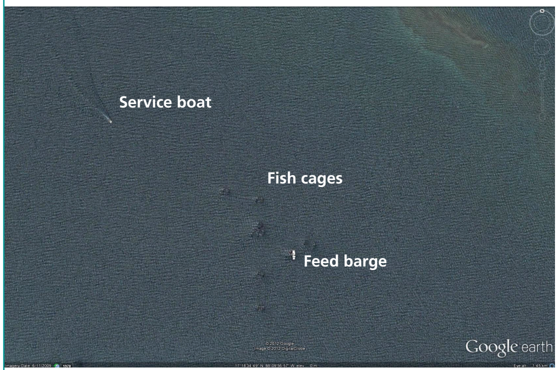
FIGURE A3.4
Selected off-the-coast mariculture sites in Google Earth

Penghu Island Taiwan Province of China. Cobia
Coordinates: 23°36′47.95″N, 119°31′29.24″E

Source/Imagery:
Image © Digital Globe
© 2012 Kingway Ltd.

Chile. Atlantic salmon
Coordinates: 43° 2′7.76″S, 73°26′42.97″W
Concession 6

Source/Imagery:
© 2012 Cnes/Spot image
Data SIO, NOAA, U.S., Navy, NGA, GEBCO
Image © 2012 Geoeye
Image © 2012 Terrametrics



Belize. Cobia
Coordinates: 17°18′28.05″N, 88° 9′57.91″W

Source/Imagery:
Imagery: © 2012 Google, Image © 2012 Digital Globe

Norway. Atlantic salmon
Coordinates: 60°41′17.31″N, 4°44′4.73″E

Source/Imagery:
Image © 2012 DigitalGlobe
Image © 2012 GeoEye

Grand Manan Island, Canada. Atlantic salmon
Coordinates: 44°43′5.26″N, 66°43′53.03″W

Source/Imagery:
Image © 2012 GeoEye

China. Ningde, Fujian Province.
Dark colour is raft culture of Phorphyra (Nori).
Bright colour structures are for cage culture of marine fin fishes.
Coordinates: 26°24′9.58″N, 119°43′45.38″E

Source/Imagery:
Image © 2012 Terrametrics;
Image © 2012 DigitalGlobe;
© 2012 Mapabc.com

4.3 Other information resources

Canada Centre for Remote Sensing (CCRS; www.nrcan.gc.ca/earth-sciences/geography-boundary/remote-sensing/11810) – remote sensing outreach materials in English and French. Includes an excellent Glossary of Remote Sensing Terms.

Census of Marine Life (http://comlmaps.org/how-to/layers-and-resources) – has produced an excellent "Layers and Resources" section on its Web site, where there are simple instructions for data download and data conversion for many of the data sets described in Chapter 3 of this publication.

Global Marine Information System (http://amis.jrc.ec.europa.eu/index_fullscreen.php) – the European Commission Joint Research Centre developed this system to provide bio-physical information related to water quality assessment and resource monitoring in coastal and marine waters. The bulk of environmental analysis relies on continuous, detailed and accurate information on relevant marine biophysical parameters as derived from optical and infrared satellite sensors.

International Ocean-Colour Coordinating Group (IOCCG; www.ioccg.org) – is a useful resource to understand ocean colour data. The IOCCG has published several useful reports, including remote sensing in fisheries and aquaculture (Forget, Stuart and Platt, 2009), and conducts and sponsors advanced training courses on applications of ocean-colour data in various developing countries.

Mapping European Seabed Habitats (MESH; www.searchmesh.net/Default.aspx?page=1658) – habitat mapping is a process that ultimately generates a habitat map to meet a specific and clearly defined need. The MESH Guide describes each of the stages in the habitat mapping process, with the final chapter providing examples of how habitat maps have been used to solve real problems. MESH webGIS presents the seabed habitat maps produced by the MESH project, with supporting layers showing coastlines and administrative areas, physical data (e.g. bathymetry, seabed geology), biological sample data, and images of the seabed obtained from a vessel.

Mediterranean Operational Oceanography Network (www.moon-oceanforecasting.eu) – has an objective to consolidate and expand the Mediterranean Sea concerted monitoring and forecasting systems, and to ensure full integration to the overall operational oceanography global ocean European capacity. The "Services" page lists a number of European ocean monitoring and forecasting services.

SAFARI Project (Societal Applications in Fisheries and Aquaculture using Remotely-Sensed Imagery; www.geosafari.org) – the IOCCG co-sponsors the project, which was developed under the umbrella of the Group on Earth Observations (www.earthobservations.org). The SAFARI Project aims to accelerate the pace of assimilation of remote sensing data into fisheries research and ecosystem-based fisheries management on a world scale.

Tools for Marine Spatial Planning (www.ebmtools.org/msptools.html) – provides steps in the marine spatial planning process; Step 5 (Define and Analyze Existing Conditions) describes the role that remote sensing can play in marine spatial planning.

4.4 Data catalogues

Based on the objectives of a proposed project, suitable remote sensing data must be chosen from the available data; in some cases acquisition of new data may be required. There are a number of data catalogues for different sensors, which enable searches for data using parameters such as area of interest, date/time of acquisition, data type and spatial resolution.

Remote sensing experts may also want to check also other parameters, such as sensor angle, as images acquired looking straight down (vertical) are often the best choice for mapping structures.

Even if the images required are available in Google Earth, image analysis requires the use of GIS or remote sensing software and access to the satellite images in their original format (see Section 4.5). Accessing the data usually requires them to be purchased. Some important catalogues are:

- **IKONOS and GeoEye-1** – GeoFuse (http://geofuse.geoeye.com), which includes a toolbar extension for ArcMap and Google Earth integration tools.
- **Rapideye** – EyeFind (www.rapideye.com/products/eyefind.htm).
- **QuickBird and WorldView** – ImageFinder (https://browse.digitalglobe.com).
- **SPOT** – SPOTCatalog (http://catalog.spotimage.com).
- **Landsat** – USGS Global Visualization Viewer (http://glovis.usgs.gov).

Other data catalogues for oceanographic data have been referred to in Section 3.1 and Section 3.2.

4.5 Data formats

a key challenge for many non-remote sensing or GIS specialists is the bewildering range of data formats and projections in which remote sensing and oceanographic data are provided. Even the most common data formats can be confusing to those who are not programmers or remote sensing and GIS specialists. Although some effort and time is required to learn how to use available data and tools, there is substantial user guidance available. Table A3.11 provides a summary of the common data formats for remote sensing and oceanographic data and references to some of the tools for viewing and converting the data.

TABLE A3.11
Summary of common remote sensing formats for operational oceanography data

Name	Description	Tools and conversion
netCDF	Network Common Data Form (netCDF) is a common, machine-independent format for representing scientific data.	ArcGIS and MGET Toolbox can be used to download and import netCDF files to ESRI GRID format. Technical information on netCDF: www.unidata.ucar.edu/software/netcdf
HDF	Hierarchical Data Format (HDF) is a common, machine-independent, self-describing format for representing scientific data. Many open source and commercial tools understand HDF.	ArcGIS and MGET Toolbox can be used to download and import netCDF files to ESRI GRID format. ArcGIS has built-in capabilities to import HDF Technical information on HDF: www.hdfgroup.org
GeoTiff	GeoTIFF is a public domain metadata standard that allows georeferencing information to be embedded within a TIFF file, such as projections, coordinate systems, ellipsoids, datums. It provides a TIFF-based interchange format for georeferenced raster imagery.	Most GIS and remote sensing software packages support GeoTIFF. Technical information on GeoTIFF: http://trac.osgeo.org/geotiff

It is also important to review the "metadata" (information about the data product) to ensure that the parameters provided by the product, format and level are understood. Metadata is often summarized in a data specification document or a text file.

4.6 Data costs

The cost of remote sensing data varies considerably, i.e. considering that some data are provided freely by international or national space and oceanographic agencies and other data are commercial products whereby a company is trying to run a profitable business based on data sales. Google Earth contains a valuable source of high spatial resolution data that can be browsed freely.

In almost all cases, the end users must make some compromises on the data they would like to use and what is practically and economically possible. For example, it may be desirable to have up-to-date, 1 m spatial resolution optical data for the entire coastal zone for a project area, but this may be prohibitive in terms of the cost and the data volumes may be hard to manage. Costs of imagery are not the same in different regions. For example, countries with satellite receiving stations often have lower government pricing for imagery. Space agencies may reduce pricing for their imagery for developing countries, e.g. ESA in Africa or the Japan Aerospace Exploration Agency for parts of southeast Asia.

It is best first to investigate what national government departments or agencies have available. The range of potential applications and size of areas of interest is an important factor. It is important to remember that there are costs associated with fieldwork, image processing and analysis, accuracy assessment and cartography that must also be considered. Labour costs will often greatly exceed the data costs, depending on the labour costs in the region. A scoping study is an essential step to determine if a proposed activity or application is economically feasible and sustainable.

As an indicative guide, the typical cost of data for some common aquaculture applications is provided in Table A3.12. The table shows the total cost for data is the cost before image processing; however, data products can be purchased at these prices (with the exception of ALOS PALSAR) with certain image processing already completed. The number of images is also estimated, although this depends on the shape of the area of interest, and many products are now available at prices based on the area of data required rather than images or "scenes". It is important to know that prices change and the market for satellite data is becoming more competitive.

TABLE A3.12

Indicative costs of satellite image data for typical aquaculture application

Mapping aquaculture structures			
Size of the area	**500 km²**		
Sensor type	**Imaging radar**		**High resolution optical**
Data type/mode	**ALOS PALSAR, fine beam**	**TerraSAR-X, StripMap**	**IKONOS or QuickBird**
Spatial resolution (m)	10	3	1
Estimated number of images	1	1	3–4
Example mapping scale	1:30 000	1:15 000	1:5 000
Cost (US$/km²)	0.5–1	5–8	10–20
Total cost for data (US$)	**500–1 000**	**5 000–8 000**	**10 000–20 000**

4.7 Software and tools

Remote sensing data cannot be considered in isolation from the systems that are required to acquire, manage, analyse and integrate data, and also to present results as the information products. Remote sensing is often viewed as a source of data for integration into a GIS, but there are increasing examples of data being incorporated into Web-based or desktop applications that are not GIS, such as Google Earth (http://earth.google.com) and CoastWatch (http://coastwatch.noaa.gov). There are a large number of software products and add-on tools that alone, or in combination, provide data management and analysis tools for available operational oceanography data.

It is important to explore different free and/or open source GIS and remote sensing software to discover if software can support the analysis that is required. An index of some open source projects is available at http://opensourcegis.org. Some good and free remote sensing options are the following:

BEAM (www.brockmann-consult.de/cms/web/beam) - toolbox and development platform for viewing, analysing and processing of medium-resolution remote sensing data from MODIS, MERIS, AVHRR, AVNIR, PRISM and CHRIS/Proba. Various data and algorithms are supported by dedicated extension plug-ins. BEAM has a good user interface and operates under the Microsoft Windows environment.

Google Earth (http://earth.google.com) – Google Earth allows users to view images obtained from satellite imagery and aerial photography on top of a 3-dimensional model of the Earth. Google Earth provides access to a range of data in the Layers section of the sidebar, including access to the Earth Gallery that contains many different types of ocean data provided by third parties (e.g. the United States Navy provides daily SST data). Many other organizations provide access to Keyhole Markup Language (KML)[15] files to explore ocean data.

Google Earth provides an easy-to-use overview of the geography of an area using satellite imagery selected by Google – high-resolution data can be especially useful for identification and localization of aquaculture structures. The drawing tools in Google Earth provide a simple way to create and annotate geographic features such as cage locations, supporting facilities and ports. Google Earth is not a comprehensive satellite image catalogue, and Google generally focuses on providing imagery over land and coastal areas, which may not be able to include some areas of interest for offshore mariculture. More images are usually available than those available in Google Earth/Maps, and it is, therefore, important to obtain a complete list of remote sensing data from one or more online data catalogues in order to choose remote sensing data for a monitoring project. An interesting example of the use of Google Earth was an assessment of the spatial distribution of fish cages and pens among 16 countries in the Mediterranean (Trujillo, Piroddi and Jacquet, 2012), which showed that 80 percent of the installations were within 1 km of the coast and that the maximum distance offshore was about 7 km.

Google Maps is a web-mapping service application and technology provided by Google, free (for non-commercial use), that powers many map-based services, including the Google Maps Web site. The simplest online mapping service provided by Google is referred to as Google My Maps.

No programming knowledge is required to make a map; simple point and click editing can be easily used to create an interactive online map. My Maps can be created collaboratively and can easily be embedded in any Web site. The only technical requirement needed for the use of My Maps is a Gmail or Google account (which are both free). For more advanced mapping applications, Google application programming interface (API) can be employed. While the maps created with the Google API can be much more advanced than those created with My Maps, a significant amount of additional coding skills are required.

Tutorials and Webinars on Google Earth and Maps:

- Ecosystem-Based Management Tools (www.ebmtools.org/search/node/Google);
- Geospatial Technologies Training Center. Making Maps the Google Way (http://extension.unh.edu/GISGPS/GISGPSTM.cfm); and
- Google Earth Web site (http://earth.google.com/outreach/tutorials.html).

ILWIS (www.ilwis.org) – free GIS software with a comprehensive set of image processing tools and capabilities for image georeferencing, transformation and making image mosaics.

[15] Keyhole Markup Language (KML) is an annotation for expressing geographic annotation and visualization within Internet-based, two-dimensional maps and three-dimensional Earth browsers. KML was developed for use with Google Earth, which was originally named Keyhole Earth Viewer. It was created by Keyhole, Inc., which was acquired by Google in 2004.

Marine Geospatial Ecology Tools (MGET; http://code.env.duke.edu/projects/mget) – provides a "geoprocessing toolbox" of more than 180 tools for coastal and marine researchers and GIS analysts who work with spatial ecological and oceanographic data. The tool is designed for ArcGIS (ESRI – Environmental Systems Research Institute), the leading commercial GIS software, which obviously limits its availability to ESRI GIS software users.
Next ESA SAR Toolbox (NEST; http://earth.esa.int/nest) - NEST is an ESA toolbox with an integrated viewer for reading, post-processing and analysing ESA and third-party synthetic aperture radar (SAR) data. NEST allows users to further develop the software package by means of a Java API. NEST is developed by Array Systems Computing, Inc., under contract with ESA.
Quantum GIS (www.qgis.org) – Quantum GIS is a user-friendly open source GIS and is an official project of the Open Source Geospatial Foundation. It runs on Linux, Unix, Mac OSX, Windows and Android, and supports numerous vector, raster and database formats and functionalities. It also provides access to standard Internet data services, such as the Web Map Service (WMS), Web Feature Service (WFS), and Web Coverage Service (WCS), and the capability to open Google Earth KML files.
Radar Tools (http://radartools.berlios.de) – tool for processing radar data. Advanced algorithms in SAR polarimetry (PolSAR), interferometry (InSAR) and polarimetric interferometry (PolInSAR) included.
SPRING (www.dpi.inpe.br/spring/english) – SPRING is a free state-of-the-art GIS and remote sensing image processing system, which integrates raster and vector data representations in a single environment. SPRING is a product of the National Institute for Space Research in the Federative Republic of Brazil.
User-friendly Desktop Internet GIS (uDIG;(http://udig.refractions.net/) – uDig is an open source Java desktop GIS application that supports data access, editing and viewing. uDig provides access to standard Internet data services, such as WMS, WFS, WCS, and the capability to open Google Earth KML files.
World Wind (http://worldwind.arc.nasa.gov/java) – a good alternative to Google Earth is NASA World Wind, which is a similar type of software but uses NASA imagery and allows the user to choose specifically the type of imagery to view.

A few examples of some of the main proprietary remote sensing software are listed below:

- ERDAS IMAGINE (http://geospatial.intergraph.com/Homepage.aspx) – one of the leading image analysis software packages developed by Intergraph.
- ENVI (www.ittvis.com/language/en-us/productsservices/envi.aspx) – this is also a leading proprietary supplier of image analysis software.
- ArcGIS (www.esri.com) – ArcGIS is the leading commercial GIS software package, offering an integrated collection of GIS software products. There are numerous extensions to the software, some of which are free such as MGET (described above).
- IDRISI (www.clarklabs.org) – as a commercial GIS and remote sensing software, it is relatively cheap, user friendly and very powerful.
- Manifold (www.manifold.net) – Manifold is a cost-effective GIS software package that can be used to integrate a variety of oceanographic data in available formats.

5. Demonstration products and case studies

Demonstration products and case studies in the subsections below are relevant to the safe environment and healthy environment parameters that can be derived from remote sensing data. The overall aim is to introduce the types of products that can support offshore mariculture and the processing steps and software tools used.

5.1 Wave heights and winds

Objective

The objective is to demonstrate how the data sets of wave heights and winds can be analysed to provide information on suitable aquaculture areas using threshold ranges for individual typical aquaculture structures.

Data

The data sets used to create demonstration products are described in Table A3.13 and Table A3.14. For the purpose of developing the demonstration map products, additional data included the EEZ Maritime Boundaries Geodatabase (Version 5, 1 October 2009) from www.vliz.be/vmdcdata/marbound, and coastline data and national boundaries from ESRI Map and Data 2008 (www.esri.com).

TABLE A3.13

SWH suitability demonstration data

Data set	AVISO significant wave height; downloaded using MGET (see processing section)
Format	NetCDF
Download size	~1 MB
Spatial extent	Global
Spatial resolution	1 degree (~90 km)
Timeliness/time period	Available "daily" data from June 2008 (total of four products)

TABLE A3.14

Wind suitability demonstration data

Data set	AVISO surface wind; downloaded using MGET (see processing section)
Format	NetCDF
Download size	~1 MB
Spatial extent	Global
Spatial resolution	1 degree (~90 km)
Timeliness/time period	Available "daily" data from June 2008 (total of four products)

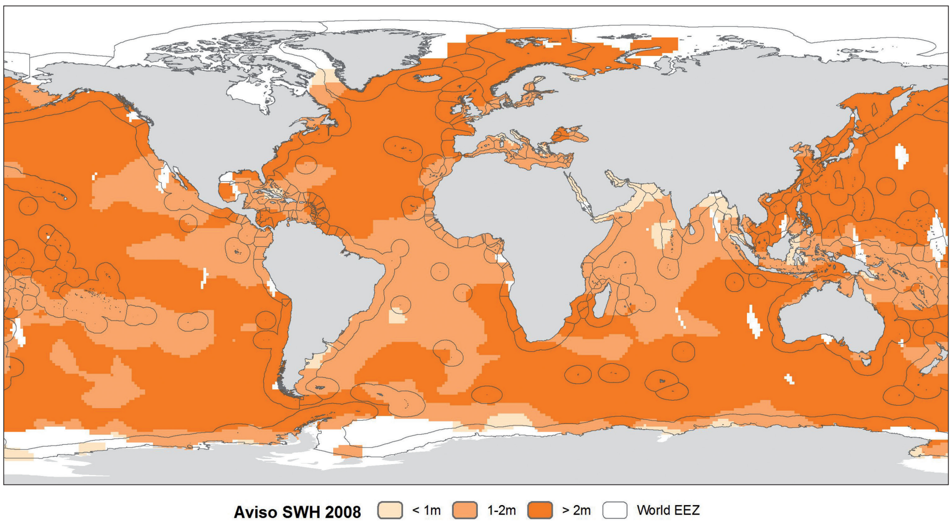
Processing

The image processing steps to create the demonstration suitability products are similar to the ones described in more detail later in section 5.2. The software used for processing and analysis of SWH and wind data was ESRI ArcGIS 9.3. The AVISO data were downloaded and converted from Hierarchical Data Format (HDF) to ESRI GRID using MGET. AVISO data are daily, and so a time range was specified as part of the MGET download process, which selected SWH and wind data for the month of June 2008. The daily data available in June 2008 were only for four days (4, 11, 18 and 25 June). Based on standard ArcGIS functions and the Spatial Analyst extension, the mean value was calculated. For the purposes of demonstrating the contents of the data, the SWH were arbitrarily classified into three simple classes: < 1 m; 1–2 m; and > 2 m. Likewise, global sea surface winds were also classified into three simple classes: < 2 m/s; 2–5 m/s; and > 5 m/s.

Results

Two demonstration products are shown in Figure A3.5 and Figure A3.6. Figure A3.5 shows the global SWH for June 2008 according to three simple classes (< 1 m; 1–2 m; and > 2 m). The classes in the map indicate areas where waves may be problematic for offshore mariculture, e.g. the coasts of the Republic of Chile, the Republic of Namibia and the Republic of South Africa, and the Kingdom of Norway. However, it must be stressed that the spatial resolution of the data is coarse (1 degree or ~90 km), and, in this example, the time period of the data is not a long-term or seasonal average. The strength of the data is that it provides a chance to explore and "screen" areas before undertaking more detailed studies.

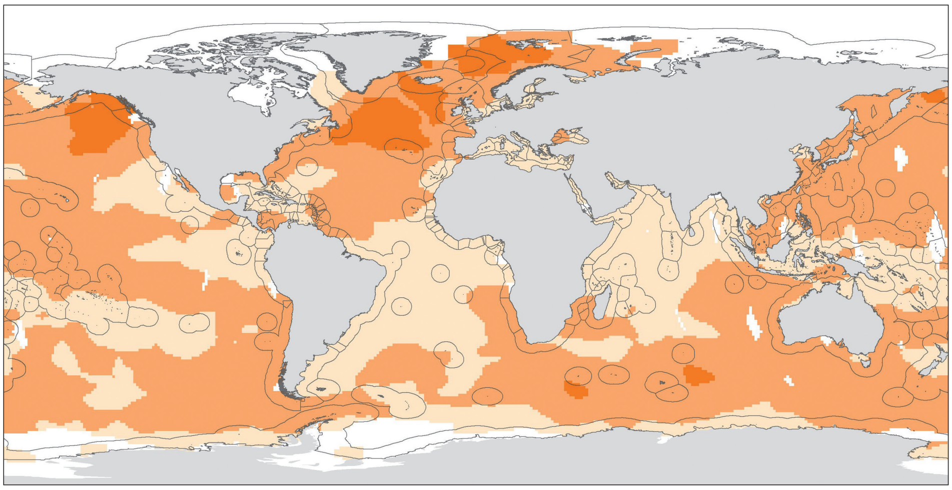
FIGURE A3.5
Global average significant wave height (metres) in June 2008



Source: AVISO (2010).

Figure A3.6 shows the global sea surface winds for June 2008 according to three simple classes (< 2 m/s; 2–5 m/s; and > 5 m/s). The pattern is similar to the SWH data, as would be expected, and again is indicative of areas that may be too exposed for offshore mariculture. Depending on the thresholds selected, more detailed patterns in SWH and surface winds may be identified, within the constraints of the resolution of the data. While some offshore fully exposed areas in Figures A3.5 and A3.6 could be considered as suitable based on significant wave height and sea surface winds, offshore mariculture development is most likely to take place relatively close to coasts within the boundaries of the EEZs.

FIGURE A3.6
Global average sea surface winds (metres sec-1) in June 2008



Source: AVISO (2010).

5.2 Sea surface temperature and productivity

Objective

The objective is to demonstrate how available SST and chlorophyll-*a* concentration data sets can support a suitability assessment for individual species and integrated multitrophic aquaculture. The suitability assessment is based on aquaculture species using threshold ranges.

Data

The data sets used to create demonstration products are described in Table A3.15 and Table A3.16. For the purpose of developing the demonstration map products, additional data included the EEZ Maritime Boundaries Geodatabase (Version 5, 1 October 2009) from www.vliz.be/vmdcdata/marbound, and coastline data and national boundaries from ESRI Map and Data 2008 (www.esri.com).

TABLE A3.15
Sea surface temperature suitability demonstration data

Data set	Aqua MODIS Seasonal Climatology Sea Surface Temperature (http://oceancolor.gsfc.nasa.gov/cgi/l3)
Format	PNG image, HDF Standard Mapped Image, HDF Binned
Spatial extent	Global
Download size	25–30 MB (compressed file)
Spatial resolution	4 km and 9 km
Timeliness/time period	Seasonal climatology data averaged for the period 2002–2009
Attributes	SST value in degree °C

TABLE A3.16

Chlorophyll-*a* concentration suitability demonstration data

Data set	**ACRI-ST InfoceanDesk environment monitoring service (http://hermes.acri.fr)**
Format	GeoTIFF (geographic)
Download size	50–100 MB (compressed file)
Spatial extent	Global and custom region
Spatial resolution	4.6 km
Timeliness/time period	Seasonal climatology data averaged for the period 1998–2009
Attributes	Chlorophyll-*a* concentration in mg/m^3

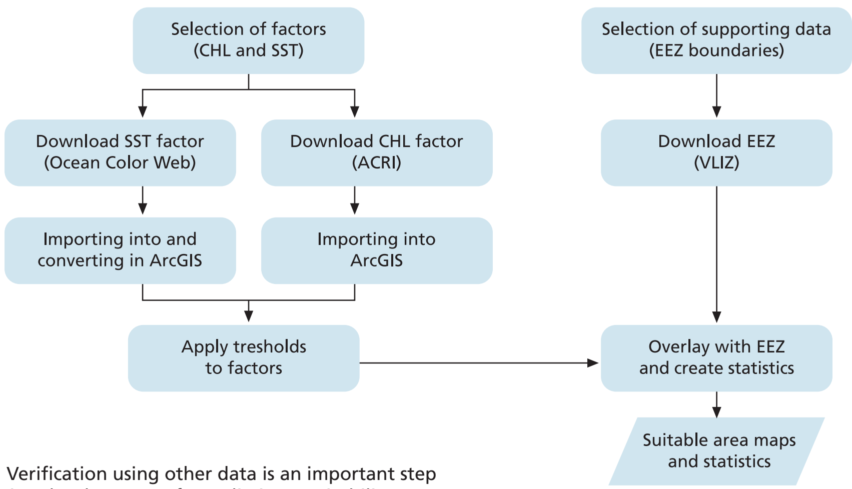
Processing

The image processing steps to create the demonstration suitability products are shown in Figure A3.7. The software used for the processing and analysis was ESRI ArcGIS 9.3.

The first step was to select the factors required for the analysis – chlorophyll (CHL) and SST. The chlorophyll-*a* concentration data were provided by ACRI and in GeoTIFF format so that they could be opened directly in ArcGIS. The SST data from OceanColorWeb were converted from HDF to ESRI GRID using MGET toolbox. Based on standard ArcGIS functions and the Spatial Analyst extension, thresholds described in Table A3.17 were applied to the data. For more information on the conditions and issues for cultured species, refer to the FAO cultured species online database (www.fao.org/fishery/culturedspecies/search/en). Finally, the EEZ boundaries data sets were downloaded and overlain with the analysed CHL and SST data, using ArcGIS, to produce the suitable area maps and data.

FIGURE A3.7

Image processing steps to create offshore mariculture suitability map products



Note: Verification using other data is an important step following development of a preliminary suitability map

TABLE A3.17
Example thresholds applied to sea surface temperature and chlorophyll-*a* concentration data

Species	Suitability criteria	Value
Cobia (*Rachycentron canadum*)	SST long-term maximum and minimum	26–32 °C
Atlantic salmon (*Salmo salar*)	SST long-term maximum and minimum	8–16 °C
Blue mussel (*Mytilus edulis*)	SST long-term maximum and minimum	5–20 °C
	Chlorophyll-*a* concentration monthly averages	> 1 mg/m^3

Results

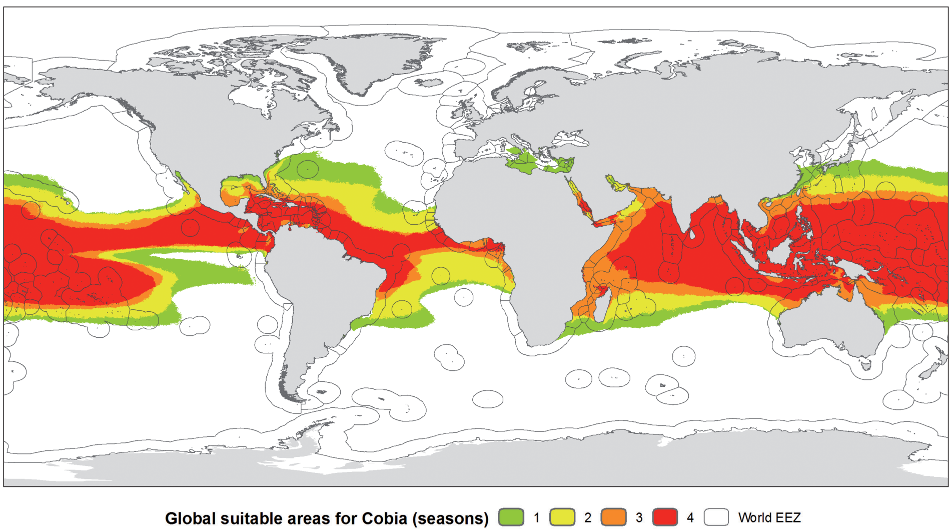
A series of demonstration products are shown in Figures A3.8 to A3.10.

Figure A3.8 shows the global areas suitable for cobia (*Rachycentron canadum*); the different SST range for this species providing a range focuses on tropical waters. According to FAO, the largest producer of this species is the People's Republic of China (www.fao.org/fishery/culturedspecies/Rachycentron_canadum/en); however, the temperature levels are considered more suitable in tropical waters.

Figure A3.9 shows the global areas suitable for Atlantic salmon (*Salmo salar*), and follows the distribution of the global Atlantic salmon aquaculture, with suitable areas being dominated by the Kingdom of Norway, the Republic of Chile, Scotland and Canada. While the offshore fully exposed areas in this figure and in Figures A3.8 and A3.9 are suitable based on SST, it is not likely that they will be developed for mariculture in the near future for economic, technical and jurisdictional reasons. Offshore mariculture development is most likely to take place relatively close to coasts within the boundaries of the EEZs shown in these and other figures. The classes in the map reveal the number of seasons where the temperature thresholds were met - the optimum being all four seasons.

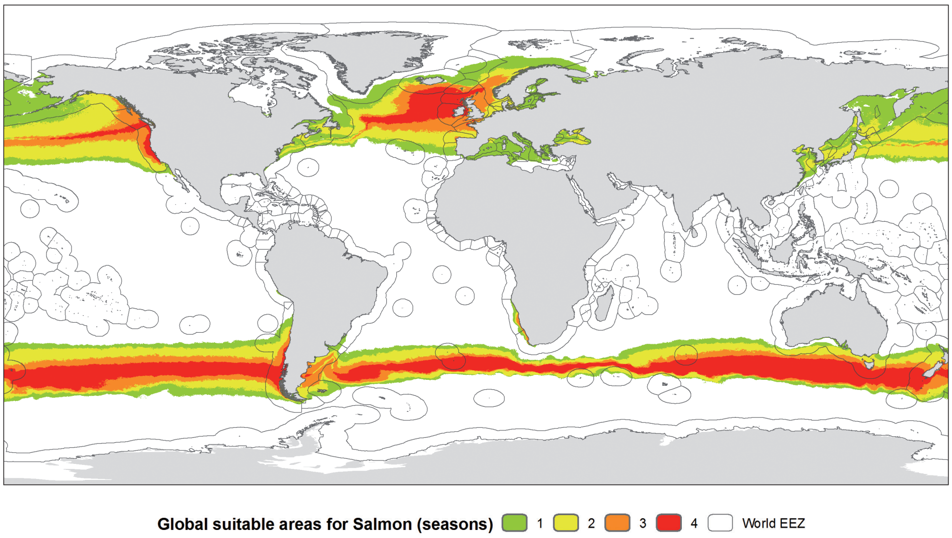
Figure A3.10 shows the global areas suitable for blue mussel (*Mytilus edulis*), which confirms some of the known cultivation areas, e.g. the Republic of Chile where a close relative of the blue mussel, *Mytilus chilensis*, is cultivated. The global analysis also indicates that the coast of the Republic of Namibia and the western coast of the Republic of South Africa are suitable, based only on SST and chlorophyll-*a* concentration data.

FIGURE A3.8
Global area suitable for cobia (*Rachycentron canadum*) based on sea surface temperature (26–32 °C)



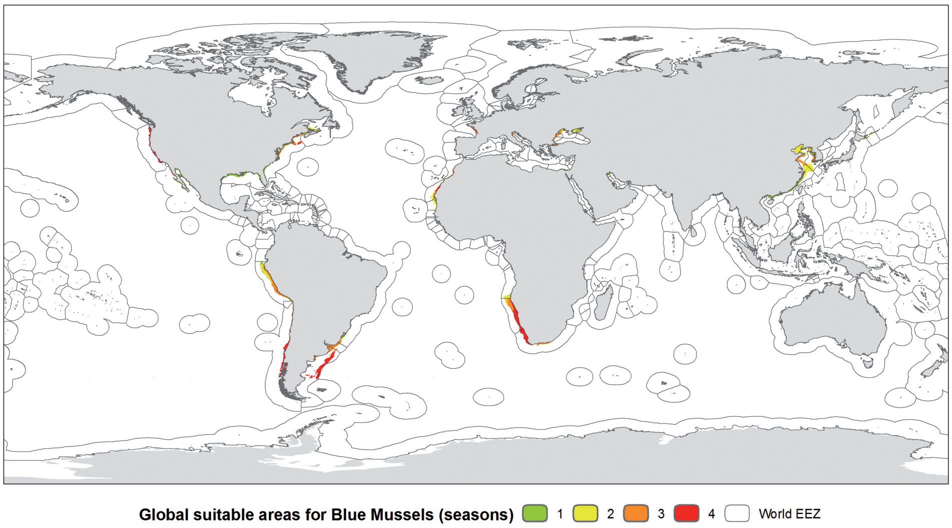
Source: Aqua MODIS Seasonal Climatology Sea Surface Temperature (http://oceancolor.gsfc.nasa.gov/cgi/l3)

FIGURE A3.9
Global area suitable for Atlantic salmon (*Salmo salar*) based on SST values from 8–16 °C



Source: Aqua MODIS Seasonal Climatology Sea Surface Temperature (http://oceancolor.gsfc.nasa.gov/cgi/l3)

FIGURE A3.10
Global area suitable for blue mussel (*Mytilus edulis*) based on sea surface temperature (5–20 °C) and chlorophyll-*a* concentration (>1 mg/m³)



Sea surface temperature data source: Aqua MODIS Seasonal Climatology Sea Surface Temperature (http://oceancolor.gsfc.nasa.gov/cgi/l3)

Chlorophyll-a concentration data source: ACRI-ST INFOCEAN-DESK environment monitoring service (www.myocean.eu.org)

Note: As shown in Figure A3.10, the combination of sea surface temperature and Chlorophyll requirements restricts the distribution of suitable areas for blue mussel. The EEZ boundaries were not used as a mask.

A GIS is more than simply a tool for making maps, as it can also be used to produce quantified data on suitable areas within an EEZ. For example, Table A3.18 reports the EEZ area of several countries suitable for cultivating Atlantic salmon (*Salmo salar*) in 1, 2, 3 or 4 seasons according to the SST criteria used to produce Figure A3.8.

TABLE A3.18

Number of seasons the EEZ for selected countries is suitable for Atlantic salmon (*Salmo salar*) according to sea surface temperature

	Suitable area km^2 (seasons)			
Country	**1**	**2**	**3**	**4**
Canada	2 206 800	1 098 100	825 300	207 600
Chile	941 200	1 038 200	665 200	761 300
Namibia	135 900	53 200	63 500	347
Norway	3 933 800	1 559 600	1 285 300	8 900

5.3 Monitoring algal bloom development (Republic of Chile)

Original publication reference: Stockwell, A., Boivin,T., Puga, C., Suwala, J., Johnston, E., Garnesson, P. & Mangin, A. 2006. Environmental information system for harmful algal bloom monitoring in Chile, using earth observation, hydrodynamic model and in situ monitoring data. (available at www.esa.int/esaEO/SEMUS5AATME_economy_0.html).

Spatial tools: Ocean colour satellite imagery, hydrodynamic model, Web development

Main issues addressed: Harmful algal blooms and aquaculture

Duration of study: 1 year (January 2005 to February 2006)

Personnel involved: Thomas Boivin, Alan Stockwell, Cristian Puga, Jason Suwala, Erin Johnston, Antoine Mangin, Philippe Garnesson and Loredana Apolloni

Target audience: Marine aquaculture industry

Introduction and objectives: Hatfield Consultants (Hatfield), in collaboration with ACRI-ST and Apolloni Virtual Studios (AVS), collaborated on a project called "Integrating Earth Observation into Aquaculture Facilities Monitoring in Southern Chile", also referred to as the "Chile Aquaculture Project" (CAP). The CAP project was funded by ESA and conducted with Mainstream Chile, part of the Norwegian holding company CERMAQ, a world leader in salmon production.

The objective was to demonstrate integrated application of remote sensing data and modelling to provide advanced warning of potentially harmful algal blooms (HABs) so that their impacts can be minimized by the aquaculture industry. The monitoring of the conditions that indicate a high HAB risk can provide sufficient time for mitigation measures to be taken by farmers to help reduce potential losses. Long-term data can help improve the site selection process for new facilities.

Data: Several information sources were used to develop a prototype of an HAB warning system:

- Remote sensing products were provided by ACRI-ST. Chlorophyll-*a* concentration and Secchi depth transparency maps were generated on a daily basis from merged MERIS and MODIS data. Daily SST data were acquired from MODIS with in situ data from buoys.
- In situ environmental data were provided by Mainstream Chile.
- Oceanographic, meteorological and land GIS data were collected by Hatfield.

Methods: Using these inputs, an oceanographic currents and tidal model was developed, which in combination with transparency and chlorophyll-*a* products was the basis for development of a HAB risk/warning map.16 The combination of ocean colour data from different sensors and daily SST meant that product delivery was possible on a daily basis, dependent on cloud cover.

Results: The image processing system and modelling were integrated to produce automatic products of chlorophyll-*a*, SST and Secchi depth. The products were integrated with a GIS to build easy-to-interpret maps, which, along with tabular data, were also displayed via a Web portal that was updated each day. The end user could choose the level of detail required by selecting overview maps of the aquaculture production area (e.g. Chiloe Island area) or by selecting specific salmon farm sites to analyse available data. An example of the Web portal page is shown in Figure A3.11, which shows an overview map with a 15-day average of chlorophyll-*a* concentration.

Validation using in situ and other data enabled accuracies to be estimated as follows:

- chlorophyll-*a*: within 15 percent;
- SST: within 0.5 °C;
- Secchi depth: ± 2 m (after algorithm recalibration);
- tide elevation from model: 10 cm at the Puerto Montt control point (astronomical tides); and
- surface current: estimated to be within 1 m/s (but with few means of validation).

Discussion and recommendations: According to the needs of users and the state of the technology, the main focus for HAB warning is on the delivery of chlorophyll-*a* data and on Secchi depths (SST is obviously of importance as well as to support modelling). Based on the CAP experience, there was a need for improvements in the accuracy and quantification of the error for the products. Secchi depths should be within an error of 2 metres (± 1 m).

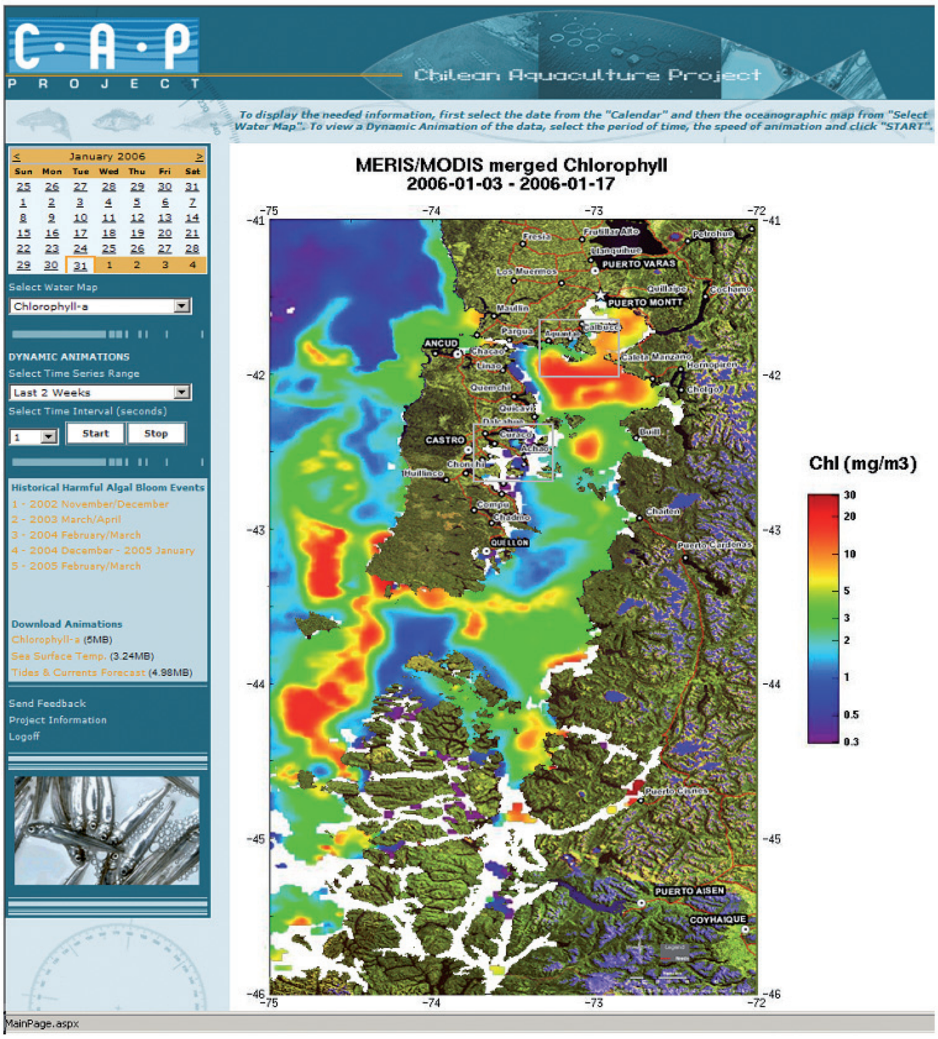
In addition to HAB warnings, another recommendation was the exploitation of available ocean colour remote sensing data to derive maps of statistics of chlorophyll-*a* persistence, variability and other statistical parameters at high resolution (e.g. 1 km spatial resolution). This type of climatology information is extremely valuable for site selection for aquaculture production areas. Also, to improve the understanding of the evolution of the environmental parameters, automatic procedures could strongly benefit the system; for example, chlorophyll-*a* front extraction by local gradient computations and quantification of differences between one daily scene and the previous scene(s).

Finally, for users there is a real need for derivation of a synthetic "HAB index" that includes all relevant environmental components. This synthetic HAB index could be expressed in the form of a very simple graphic (ideally three colours from green to red, meaning non-risk to high risk).

The CAP project provided important information on HAB occurrences in the key aquaculture regions of southern Republic of Chile, which proved to be extremely valuable to the industry and local government. Long-term monitoring of HAB information is important to help protect the aquaculture industry from possible losses in production, which can be significant in the event of a major HAB event.

[16] HABs and normal CHL are not separated or detected directly. The inputs are combined to determine HAB risk.

FIGURE A3.11
Chile Aquaculture Project Web portal – main page



Source: Hatfield Consultants (2009).

5.4 Coastal fisheries and aquaculture structure mapping in the Lingayen Gulf, the Republic of the Philippines

Original publication reference: 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. 2004. 45 pp. (also available at www.fao.org/docrep/007/y5319e/y5319e00.htm).

Spatial tools: Remote sensing

Main issues addressed: Inventory and monitoring of aquaculture and the environment

Duration of study: Six months; the study began in 2003 and ended in 2004

Personnel involved: (i) Remote sensing specialist with a working knowledge of remote sensing applications in fisheries and aquaculture (FAO Remote Sensing Officer) assisted with the design of the study and analyses and managed the project; full time. (ii) Fisheries and aquaculture specialist with a working knowledge of GIS and remote sensing applications (FAO Aquaculture Officer) assisted with the design of the study; part time for the duration. (iii) Digital image processing specialist (consultant and professor) provided modelling, image processing and analyses; full time. (iv) Philippine aquaculturist, who wrote the description of the structures (fish pens, cages and traps) and played a key role in ground verification; part time for the duration. (v) Field verification personnel from the Bureau of Fisheries and Aquatic Resources of the Philippines (four staff); full time for short duration. (vi) Advisers at large (four advisers), who provided data and advice from time to time.

Target audience: The study is aimed at the general fisheries and aquaculture public, governmental administrators and planners, and remote sensing and GIS specialists.

Objective: The objective of this FAO-led study was to test, under operational conditions, a methodology for inventory and monitoring of shrimp farms using radar satellite imagery. The study focused on various types of structures (onshore fish ponds, fish pens in the tidal zone, and offshore cages and traps in the Lingayen Gulf, the Philippines) and aimed to compare the suitability of different types of imagery.

Data: Radar data are known to offer unique capabilities for mapping shrimp farms, not only for their inherent all-weather capabilities (important in tropical and subtropical areas), but also for the way radar interacts with pond dykes (Travaglia, Kapetsky and Profeti, 1999). Pond dykes are distinguishable from surrounding water surfaces and from the much lower dykes surrounding rice paddies and other flooded areas. The study area was covered by two ERS-2 SAR images acquired in descending and ascending orbits in December 2002 with a spatial resolution of 25 m – see Dean and Populus (2013) for description of satellite orbits. Orbit direction is relevant because it influences the characteristics of the SAR images, and aquaculture features are enhanced in a complementary way. A RADARSAT-1 Fine Mode SAR image was acquired in February 2001 with a ground resolution of 9 m, which covers a smaller area than the ERS images but covered the majority of the area where the aquaculture and fisheries structures are located.

Methods: The images were geometrically corrected. A fish pond dyke reflects back a large amount of the incident radar energy, but this varies with the angle between the object and the direction of the incident beam. Hence, if a dyke is parallel to the radar beam it may not be detected, which is why ascending and descending orbits were acquired. The other aquaculture and fisheries structures influence the radar signal in a similar way. The vertical sides of fish cages, pens and traps, emerging from the water surface, create a corner reflector effect that allows them to be identified.

Classification (feature extraction) was conducted using visual interpretation, as described in Dean and Populus (2013). This means that a skilled image analyst manually identified and digitized the boundaries of the aquaculture structures. The validation data for an accuracy assessment was collected during field surveys by a team of the Bureau of Fisheries and Aquatic Resources of the Philippines.

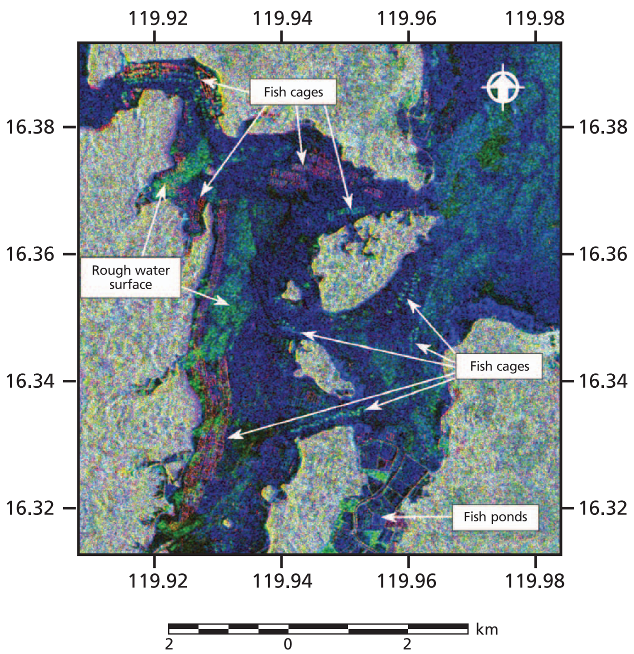
Results: The presence of the elevated surrounding dykes ensured straightforward visual interpretation. The area having fish ponds in 2002 was compared with the area mapped in 1977 topographic maps; the area had increased by 60 percent, but some of the ponds mapped in 1977 had been converted to other uses.

Fish cages were detected in all images; however, environmental conditions, such as windy conditions causing rough sea surfaces, at the time of scene acquisition negatively affect their detectability. Fish cages may be of several shapes (square, rectangular, circular) and made of various materials. Those mainly made of metal have a brighter appearance on SAR images, a common detection characteristic in radar technology. Fish traps that appeared on the sea surface were separated into two categories: offshore traps and traps inside major rivers. The area occupied by fish traps was calculated to estimate their extension. In many cases, only the central structure of the traps is visible in the images. However, because of their small size, the uncertainty on identification of traps was higher than that of the other structures.

An example of the RADARSAT-1 imagery and the images ability to map aquaculture structures is provided in Figure A3.12.

The accuracy of the visual interpretation procedure was close to 100 percent for all structures except for fish cages and traps, as they may have been moved in the time interval between the image acquisition and the field verification. The clear appearance of fish cages in the SAR imagery permitted a 90 percent estimated mapping accuracy. Mapping accuracy for fish traps was estimated at 70 percent (for fish traps of the type that had potential to be detected by remote sensing).

FIGURE A3.12
Interpreted RADARSAT-1 SAR image and the resulting map of the aquaculture and fisheries structures



Source: Travaglia *et al.* (2004).

Discussion and recommendations: RADARSAT fine mode imagery provided the best "detectability" for all aquaculture and fisheries structures considered in this study and, therefore, allowed them to be inventoried and monitored with greater accuracy. ERS imagery enabled successful mapping of fish ponds and fish cages, but failed to map fish pens and fish traps. For mapping fish ponds and fish cages, using images from ascending and descending orbits acquired within a limited time interval is recommended.

Following this study, the same authors verified the possibility of integrating optical data into monitoring coastal fisheries and aquaculture structures (G. Profeti, personal communication, 2012). They examined high-resolution optical data (e.g. IKONOS, GeoEye, QuickBird, WorldView and SPOT HRV) acquired over the study area in the same time period in which radar data were acquired, but no suitable archive data were found, even if the period was extended to two years. The lack of available data may be due to persistent cloud cover, or because commercial operators may not acquire data in many areas where commercial sales will not be made. The availability of optical and radar data cannot be assumed, and in many cases acquisitions must be carefully planned and ordered.

Since the study was completed, there have been significant developments in imaging radar as described in Dean and Populus (2013), especially the new high-resolution sensors, and there are cost-effective options for imagery. The potential application of radar includes monitoring of bluefin tuna cages in the Mediterranean Sea fishing grounds. A recent study by Pereza et al. (2011) demonstrated that floating cages towed by vessels to transport live tuna towards inshore farms have a unique signature in the radar images based on their distinctive texture pattern and position with respect to the towing vessel.

5.5 Use of remote sensing for mapping seagrass

Original publication reference: Pasqualini, V., Pergent-Martinia, C., Pergenta, G., Agreila, M., Skoufasb, G., Sourbesc, L. & Tsirikad, A. 2005. Use of SPOT 5 for mapping seagrasses: an application to Posidonia oceanica. Remote Sensing of Environment, Vol. 94: 39-45.

Spatial tools: SPOT-5 multispectral imagery, GIS

Main issues addressed: Environmental impacts of aquaculture; management of aquaculture together with fisheries

Duration of study: Not reported

Personnel involved: Not described

Target audience: Coastal management community

Introduction and objectives: *Posidonia oceanic*a is the dominant seagrass in the Mediterranean Sea (Marba *et al.*, 1996). *P. oceanica* plays an important role in many coastal processes, contributing to sediment deposition and stabilization and to attenuating currents and wave energy (Fornes *et al.*, 2006). Seagrass meadows are also considered to be among the most productive ecosystems, supporting diverse flora and fauna and providing nursery and breeding grounds for many marine organisms (Francour, 1997; Hemminga and Duarte, 2000). *P. oceanica* is a slow-growing climax species17 that forms large stable meadows, but there is evidence of decline in many areas as a result of warming sea temperatures and pollution (Marba et al., 1996; Marba and Duarte, 2010).

Potential sites for coastal aquaculture may affect ecologically sensitive areas such as coral reefs and seagrass beds, but offshore sites may still need to consider potential impacts on sensitive areas such as *P. oceanica* meadows and apply the precautionary principle. Maps of the distribution of *P. oceanica* are required for effective management and conservation.

A wide range of methods may be used for mapping seagrasses (McKenzie, 2003), including optical satellite and aerial remote sensing and acoustic sampling. Generally, the key challenges for mapping *P. oceanica* using optical images are: (i) limited light penetration to the maximum depth of *P. oceanica* distribution (about 40 m); and (ii) spatial resolution of the sensor in relation to the potential patchy distribution of P. oceanica with substrates such as rock and sand. Aerial photographs (Pasqualini et al., 1998, 2001), Compact Airborne Spectrographic Imager (CASI) (Mumby and Edwards, 2002) and IKONOS imagery have been employed in recent studies to map seagrasses.

[17] Climax species are plant species that will remain essentially unchanged in terms of species composition for as long as a site remains undisturbed.

Pasqualini *et al*. (2005) investigated the potential of SPOT-5 optical satellite imagery for mapping *P. oceanica* in Zakynthos Marine National Park (Mediterranean Sea, the Hellenic Republic). The objective of the study was to examine the potential of different spatial resolution SPOT-5 images to map seagrass in Laganas Bay, part of the National Park. The bay is 12 km long and 6 km wide with seagrass known to range from the near surface to approximately 30 m depth. Four types of community and seabed type are found: mobile sediments (silts and sands), communities on hard substrates (including shingle), continuous beds of P. oceanica, and mosaics of beds (on a mat, rock or sand).

Data: SPOT-5 imagery has four spectral bands: green (0.50-0.59 µm); red (0.61-0.68 µm; near infrared (0.78-0.89 µm); and mid-infrared (1.58-1.75 µm). The first three bands have a spatial resolution of 10 m while the mid-infrared has a resolution of 20 m. A combination of multiple SPOT-5 images acquired at the time also provides multispectral imagery enhanced to 2.5 m spatial resolution. Because there is little penetration of longer infrared wavelengths through the water column, only the green and red visible bands were used at 10 m and 2.5 m resolution in a SPOT-5 imagery acquired on 1 September 2003.

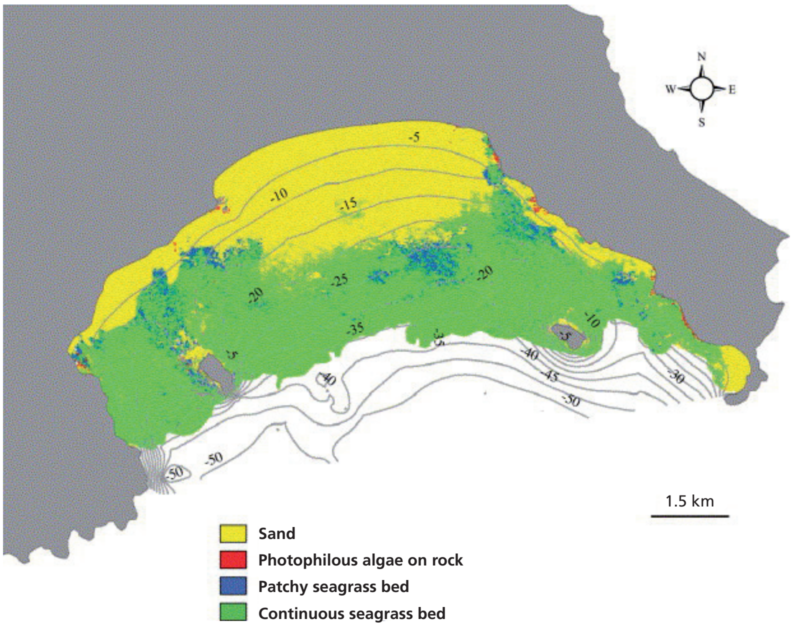
Methods: The processing of the two SPOT images was carried out using Multiscope software (Matra Systems and Information). The terrestrial part was masked in order to optimize the distinction between communities and types of seabed in the marine part. Principal component analysis was applied to the two bands in each image. A supervised classification was then applied separately to the depth layers 0–10 m and 10–20 m so as to minimize any confusion between classes due to depth. This technique was previously applied on aerial photographs (Pasqualini *et al.*, 1997), and caution is required because it can result in classification bias near the depth limit boundary.

Classification training data were 189 field observations points obtained by scuba diving or by observing the seabed from a boat. These data enabled the communities and types of seabed in Laganas Bay to be identified. The accuracy of the habitat maps was determined using the overall accuracy. Subsequently, some manual corrections were made, for example, masking beyond the maximum possible depth of P. oceanica beds.

Results: The classification results revealed the predominance of *P. oceanica* beds in the bay, from the surface down to a depth of about 30 m. The map at 10 m resolution is shown in Figure A3.13 – a large area of sand occupied the northeast of the bay down to a depth of 20 m, while the southeast and northwest were occupied by large rocky slabs, colonized by photophilous algae. These rock-dwelling photophilous algae were absent beyond the 10 m isobath. On the maps with a resolution of 2.5 m, substantial areas of patchy seagrass beds were identified over the whole of the depth range studied.

Discussion and recommendations: The overall accuracy of the habitat maps ranged from 73 to 96 percent. The 10 m image provided a better overall accuracy for each depth band. Sand was mapped least accurately. The patchy seagrass beds were mapped with a higher degree of accuracy by the SPOT 2.5 m because the improved spatial resolution revealed the patchiness of the habitat.In summary, SPOT image classification was considered a valuable method for a rapid identification of seabed types. The large image size of SPOT-5 makes it an attractive tool for the management of coastal waters; however, SPOT-5 and several other sensors lack a blue spectral band. Since the study by Pasqualini *et al.* (2005), WorldView-2 was launched in 2009 with a 1.8 m resolution visible spectrum "coastal band" (400–450 nm) that penetrates the water to greater depth. This sensor offers potential for improved and detailed mapping of *P. oceanica* beds. This type of remote sensing classification could also be useful to inventory commercial culture of seaweeds.

FIGURE A3.13
Main benthic assemblages and bottom types at Laganas Bay, Greece, based on classification of a SPOT5 image (10 m resolution)



Source: Pasqualini *et al.* (2005).

In general, satellite-based methods offer most potential in shallow waters where significant *P. oceanica* losses caused by human impact are expected to occur. The use of remote sensing, coupled with GIS, could be of immense value to supporting improved coastal management decisions and in environmental impact assessments for assessing the potential impacts of aquaculture on coastal environments on *P. oceanica* meadows.

6. Conclusions

Advances in remote sensing systems, communications technology and computer processing mean that oceanographic remote sensing data are becoming more accessible, and these products should be useful for offshore mariculture applications. Many obstacles that had once hindered the application of remote sensing are now less problematic, including affordability, information content, timeliness and delivery frequency. Several important information requirements related to a healthy environment for the growth and well-being of cultured organisms can be met through remote sensing, including temperature, primary productivity and turbidity. Information on the safety of aquaculture structures can also be provided from processed satellite radar altimetry and coastal HF radar, although the freely available wave, wind and currents products have a spatial resolution that is too coarse for most applications.

For an offshore mariculture global and regional "site suitability assessment", remote sensing data can provide important data for integration and analysis within a GIS. Suitability assessment requires integration of additional data sets, such as bathymetry, accessibility (distance to ports), and management related information such as infrastructure. "Site selection and zoning" requires higher spatial resolution imagery products, and several freely available data sets include chlorophyll-*a* concentration, turbidity and SST. Suitable data on currents, waves and winds require engaging with suppliers such as AVISO, HYCOS consortium, or any agency managing HF radar. "Monitoring" applications for offshore mariculture usually demand at least daily observations and information reports on the environmental status (e.g. currents or chlorophyll-*a* concentration), which can be a challenge because of cloud cover for optical satellite sensors. Currents are highly variable, so the hourly data that are possible from HF radar is most appealing. For ocean colour observation, such as chlorophyll-*a* concentration, no single satellite provides daily coverage, which means that information services such as the ACRI-ST InfoceanDesk environment monitoring service (www.myocean.eu.org) are based on integration of several satellites.

International and national space agencies, recognizing the user requirements for satellites at the mission design stage, are set to launch tandem or constellation missions (e.g. Sentinel-1 in 2013; RADARSAT Constellation in 2014) that will increase the observation frequency. However, despite progress with the technology, many potential users of remote sensing data lack access to training, support, and tools to acquire different data sets and use them to support their activities. Thanks to the efforts of several international organizations, such as the Census of Marine Life, there are many well-documented applications of remote sensing for marine applications as well as simple guides to download and convert remote sensing data. This review provides some simple options to acquire data and begin to process data for incorporation into further analysis using GIS of relevance to offshore mariculture.

In conclusion, aquaculture is practised worldwide in highly variable environments, but the biological systems and sustainable human exploitation are controlled to a greater or lesser extent by many variables that can be measured by remote sensing. It is likely that remote sensing will play a more important role in planning and management activities, and also monitoring. The unique capability of satellite remote sensing to provide regular, repeated observations of the entire globe or specific regions at different spatial scales will also become increasingly important in the context of global climate change and the EAA. The time series of information products that are operationally derived from remote sensing should be part of government assessments of climate change impacts and action plans for industry adaptation. Another related concern is ocean acidification as a result of oceans absorbing about 50 percent of the carbon dioxide released from the burning of fossil fuels, which results in an increase in ocean acidity. Remote sensing will be an important tool in future studies of ocean acidification, which will require development and validation of models along with in situ data.

7. Glossary

Electromagnetic radiation. Energy propagated through space or through material media in the form of an advancing interaction between electric and magnetic fields.

Orbit. (1) The path of a body or particle under the influence of a gravitational or other force. For instance, the orbit of a celestial body is its path relative to another body around which it revolves. (2) To go around the Earth or other body in an orbit.

Geosynchronous orbit. An orbit around the Earth whereby a satellite travels in a general west-to-east direction and completes the orbit in the same time as the Earth completes a revolution.

Incidence angle. In radar, the angle formed between an imaginary line normal to the surface and another connecting the antenna and the target.

Platform. The vehicle that carries a sensor, i.e. satellite, aircraft, balloon, etc.

Polarization. A property of an electromagnetic wave that describes the locus of the electric field vector as a function of time.

Remote sensing. The science, technology and art of obtaining information about objects or phenomena from a distance (i.e. without being in physical contact with them).

Resolution. Resolution is the ability of a sensor to distinguish two closely spaced objects or lines as two rather than one object or line. Alternately, it is the smallest object or narrowest line a sensor can detect.

Satellite. A vehicle put into orbit around the Earth or other body in space and used as a platform for data collection and transmission.

Sensor. A device that measures the electromagnetic energy that is emitted or reflected by features of the Earth's surface and converts it into a signal that can be recorded and displayed as either numerical data or an image.

Sun-synchronous orbit. The path of a satellite in which the orbital plane is near polar and the altitude is such that the satellite passes over the same latitude at approximately the same local (sun) time each day.

Wavelength. Minimum distance between two events of a recurring feature in a periodic sequence, such as the crests in a wave.

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