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Site selection for shellfish aquaculture by means of GIS and farm-scale models, with an emphasis on data-poor environments

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ABSTRACT

An integrative methodology for site selection of shellfish aquaculture that combines geographical information systems and dynamic farm-scale carrying capacity modeling was developed. The methodology determines suitable aquaculture areas through 3 stages of analysis: (i) analysis of regulatory and social spatial restrictions using GIS to generate a constraints map; (ii) a Multi-Criteria Evaluation that considers the criteria (sediment, water and ecological quality data) and constituent factors (physical, growth and survival, product quality and environmental sensitivity) to generate a final map showing the most appropriate areas using GIS tools; and (iii) detailed analysis of production, socio-economic outputs and environmental effects of suitable areas using the FARM model. The methodology emphasizes the application in data-poor environments, where there are a combination of social difficulties, data scarcity, and aquaculture expansion pressure.

The methodology was tested for Pacific oyster (*Crassostrea gigas*) suspended longline culture in the Valdivia estuary (south central Chile), in order to explore the approach and make management recommendations for potential application. The identification of 3 km^2 (7.6%) of suitable sites in the study area using a GIS approach was made considering regulatory and social constraints; growth and survival factors, physical factors, product quality factors, environmental sensitivity zones, water, sediment and ecological quality criteria, factor suitability ranges, and a final Multi-Criteria Evaluation. The final assessment of production carrying capacity at four potentially suitable sites (Niebla, Valdivia, Isla del Rey and Tornagaleones) indicates that Tornagaleones is the most promising area for shellfish aquaculture and Valdivia is satisfactory; the Niebla and Isla del Rey sites are of marginal interest. Tornagaleones shows a total potential harvest of 139.6 t over a 395 day cultivation period for the test farm, and an average physical product of 11.64. Mass balance estimation was carried out to determine the potential positive impact of the suitable sites for nutrient credit trading. Biodeposition of organic material from the longline leases was also simulated, and found to have a low negative impact on sediment quality. Eutrophication assessment results indicate that positive impacts on water quality in Valdivia and Tornagaleones sites were obtained due to high phytoplankton removal.

This methodology illustrates how GIS-based models may be used in conjunction with tools such as a farm-scale carrying capacity model to assist decision-makers in developing an ecosystem approach to aquaculture. The application of this approach provides an integrative methodology for site selection for shellfish aquaculture, despite limitations in the data available, taking into account production, socio-economic and environmental aspects.

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1. Introduction

Aquaculture is one of the fastest growing food-producing sectors, supplying approximately 47% of the world's fish supply (FAO, 2009) and is expected to dominate production by the year 2030 (Brugere and Ridler, 2004). However, this strong expansion of aquaculture has brought significant environmental and management problems, such as sediment organic enrichment and eutrophication (Holmer et al., 2005; Islam, 2005; Kalantzi and Karakassis, 2006; Mantzavrakos et al., 2007); chemical pollution from pharmaceuticals, organics, antibiotics and metals (Antunes and Gil, 2004; Boxall, 2004; Cabello, 2004, 2006; Calvi et al., 2006; Hamilton et al., 2005; Hites et al., 2004; Holmstrom et al., 2003; Lai and Lin, 2009; Mantzavrakos et al., 2007; Sapkota et al., 2008); and changes in biodiversity of endemic populations (Pusceddu et al., 2007; Soto et al., 2001; Tomassetti and Porrello, 2005; Vezzulli et al., 2008).

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As an example, the uncontrolled expansion of salmon aquaculture in Chile over two decades had, by 2006, resulted in a range of negative environmental effects such as: (i) significant loss of benthic biodiversity; (ii) localized changes in the physico-chemical characteristics of sediments; (iii) contamination by emergent chemicals such as pharmaceuticals; (iv) increases in frequency and duration of dinoflagellate blooms; (v) potential impacts of farmed fish escapees on native species; and (vi) a two to fivefold increase in abundance of omnivorous diving and carrion-feeding marine birds in salmon farm areas (Buschmann et al., 2006; Cabello, 2004, 2006; Soto and Norambuena, 2004; Soto et al., 2001).

Aquaculture managers can mitigate such environmental impacts through the incorporation of an Ecosystem Approach to Aquaculture (EAA — Aguilar-Manjarrez et al., 2010; Soto et al., 2008) into integrated coastal zone management (ICZM) plans. Applications of EAA include optimizing site selection, real-time management of aquaculture operations, estimating carrying capacity, and evaluating ecosystem resilience (Aguilar-Manjarrez et al., 2010). The prediction of suitable sites, potential production, economic outputs and environmental effects is essential in order to minimize environmental impacts and social conflicts, maximize economic return (GESAMP, 2001; Grant et al., 2008), and ensure sustainable development (Kapetsky and Aguilar-Manjarrez, 2007).

Although the research community has, over the last decade, developed methodologies such as GIS and predictive models to support decision-making for EAA (Ferreira et al., 2007a; Tett, 2007), there is a pressing need for such tools to be more directed at industry and management. Furthermore, with projected expansion in European and North American aquaculture limited to at best 2–3 million tonnes over the next decades (Olin, 2010; Varadi, 2010), the bulk of the projected 30 million t y^{-1} of additional aquatic products required to feed the world will undoubtedly be cultivated in developing countries, principally in Asia (Silva, 2010). Additionally, the gap between developed and developing countries is widening in terms of environmental legislation (e.g. the recent Marine Strategy Framework Directive — 2008/56/EC — in the European Union). It is therefore important to develop and test frameworks that incorporate site suitability (Frankic and Hershner, 2003; Longdill et al., 2008; Radiarta et al., 2008), potential production, economic outputs, and environmental externalities (Ferreira et al., 2009a, 2009b), especially under data-poor conditions.

GIS is useful for manipulating spatial aspects of aquaculture planning due to the ability to bring together many diverse and complex factors to facilitate development and administrative decisions (Ross et al., 2009). The application of GIS to aquaculture planning has been reported by many authors (e.g. Arnold et al., 2000; Buitrago et al., 2005; Kapetsky and Aguilar-Manjarrez, 2007; Longdill et al., 2008; Nath et al., 2000; Pérez et al., 2005; Radiarta et al., 2008; Rajitha et al., 2007; Ross et al., 1993; Silva et al., 1999; Vincenzi et al., 2006). Most of these applications use the Multi-Criteria Evaluation (MCE) approach to define broad sets of evaluation criteria relevant to the site selection decision problem (Hunter et al., 2006, 2007; Longdill et al., 2008; Pérez et al., 2005). However, GIS-based site selection approaches do not include dynamic models for estimation of carrying capacity and for the determination of the temporal variability of environmental effects. A range of such models are available (e.g. Bacher et al., 2003; Chamberlain, 2002; DEPOMOD: Cromey et al., 2002; FARM: Ferreira et al., 2007a; Grant et al., 2007; MOM: Stigebrandt et al., 2004; Weise et al., 2006; Weise et al., 2009).

This work aims to develop and test an integrated approach of GIS and farm-scale modelling to site selection of shellfish aquaculture, with an emphasis on application to data poor environments. The FARM model was selected for dynamic modelling because it provides all the necessary outputs, is easy to use, and has been extensively tested (EU, Ferreira et al., 2009a; USA, Ferreira et al., 2008; China, Ferreira et al., 2009a, 2009b; and Chile, Ferreira et al., 2010; Silva, 2009).

The main objectives are:

1. To develop a methodology for site selection of shellfish aquaculture, that combines spatial factors and criteria (water quality, sediment quality and ecological quality) to identify suitable areas using GIS tools, and explores production, socio-economic outputs and environmental impacts by applying a shellfish farm-scale model.
2. To test the methodology for a particular area, specific shellfish species, and culture type in a coastal area of a developing country where aquaculture management is carried out using relative paucity of data and information.
3. To make management recommendations, in order to exemplify the use of this approach to assist the decision making process and reduce socio-economic and environmental problems associated with aquaculture expansion.

2. Methodology

The general approach used in this work combines results of a three stage analysis involved in the selection of an appropriate site for shellfish aquaculture (Fig. 1). Stage One considers regulatory and social constraints of potential aquaculture sites, Stage Two uses MCE of sediment, water and ecological quality data to determine suitability for aquaculture siting, and Stage 3 is a detailed analysis using a farm-scale carrying capacity model that takes into consideration the production, socioeconomic outputs and environmental effects, building on results from Stages 1 and 2.

This site selection methodology was tested for Pacific oyster (*Crassostrea gigas*) aquaculture in a study area situated in the Valdivia estuary, south central Chile (39°52′S; 73°24′W) (Fig. 2). Pacific oysters are cultivated in small areas of the Valdivia estuary at an experimental scale (Möller et al., 2001), making it an ideal site for testing growth conditions by means of integrated modelling to support management of prospective expansion scenarios. This estuary is an example of a relatively data poor environment, where substantial pressure exists to increase aquaculture, and is an area that was close to the epicenter of two devastating earthquakes in the last fifty years, most recently in 2009. The combination of social difficulties, data scarcity, and pressure for aquaculture expansion make it an ideal system for testing the methodology developed in this paper.

2.1. Methodology and application

2.1.1. Study area

The Valdivia estuary has an area of 40 km^2 and volume of 170×10^6 m^3, a maximum depth of 18 m, and receives a mean freshwater input of 15.7×10^9 m^3 y^{-1}, mainly from the Valdivia river (Arcos et al., 2002). The climate of the area is temperate rainforest with Mediterranean influence (DMC, 2008), with an annual precipitation of about 2200 mm in Valdivia city. The estuary has a wide range of complementary and in some cases conflicting uses, including forestry terminals, fishmeal plants, commercial shipping, artisanal fisheries, salmon farming and tourism (Fig. 2). Effluents from industry, agriculture, forestry and urban sources from Valdivia city are discharged into the rivers, and constitute a major factor of pollution and deterioration of water quality. The study area includes the Valdivia and Tornagaleones rivers, Isla Mancera, east part of Isla del Rey, Niebla and Corral cities (Fig. 2). The tidal regime at the estuary mouth (bay of Corral) is semi-diurnal, with an average range of 0.8 m, ranging between 0.5 and 1.5 m (Pino et al., 1994). Tides are the main source of energy to the circulation of the estuarine system. Only a few studies and sampling campaigns have collected information on water quality, sediment characteristics, primary production, benthic fauna and

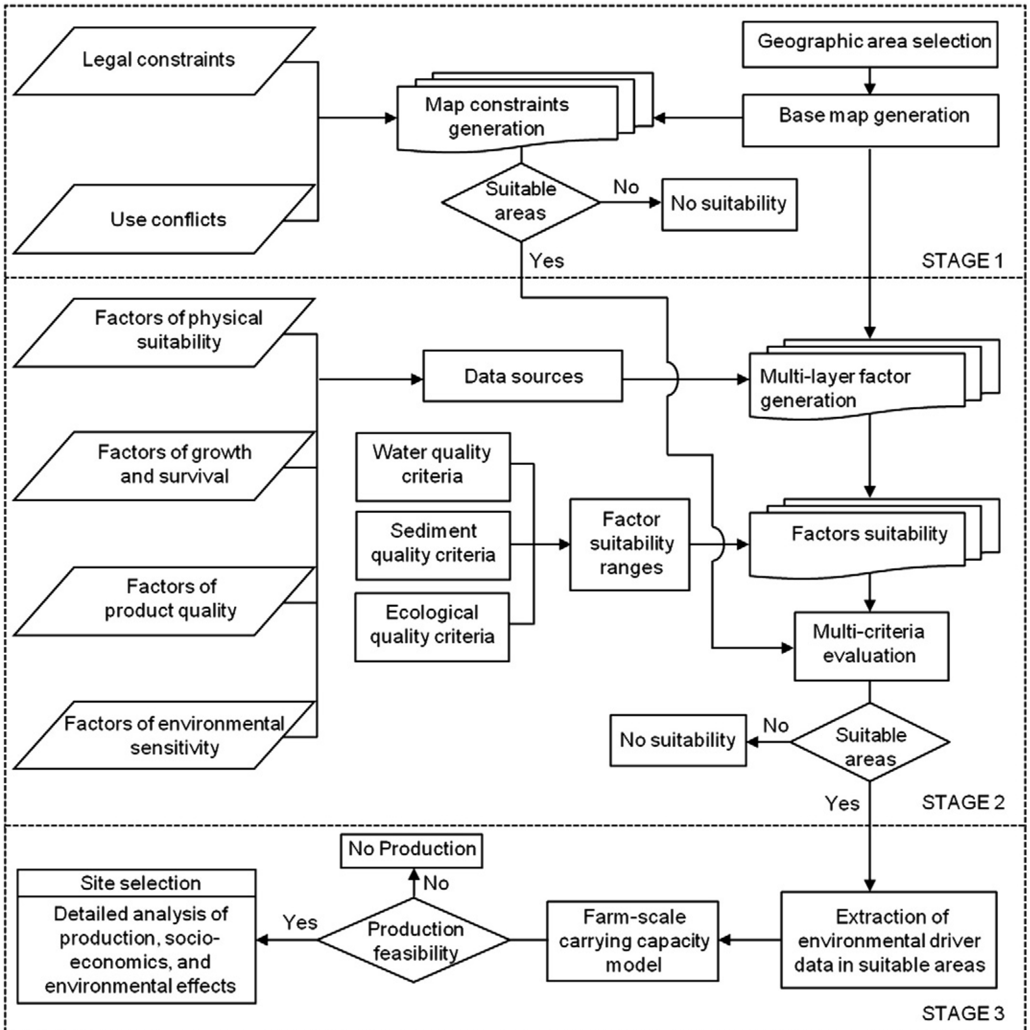

Fig. 1. Methodological flow diagram of the site selection approach for shellfish aquaculture.

pollution in the estuary (Arcos et al., 2002; Palma-Fleming et al., 2004; Ramírez, 2003; Velázquez, 2005).

2.1.2. Stage 1: regulatory and social constraints

The first stage is a suitability analysis using regulatory and social constraints, and serves to limit the study area, taking into account legal constraints and conflicting uses to shellfish aquaculture. A collection of spatial data from different sources, the generation of thematic map for each constraint and an overlay process is used to define suitable areas.

2.1.2.1. Regulatory and social constraints analysis. There are significant commercial shipping operations in the Valdivia estuary such as recreational boating, artisanal fisheries, and fishmeal and wood chips transport (Fig. 2). Additionally, two salmon farms are presently operating in the study area (Fig. 2). Marine Protected Areas (MPAs) for the controlled (by fisheries authorities) exploitation of benthic resources by artisanal fishermen are also located in the area, and are considered as an existing coastal use and societal value (MINECON, 1995). Legal constraints are related to the Unsuitable Aquaculture Areas (UAA), which are those geographic areas of national property for public use, through appropriate consultation with agencies of the alternative uses of those lands or waters, in which the State is empowered to receive and process applications for aquaculture (MINECON, 1992).

Socially conflicting uses and constraints to shellfish aquaculture suitability zoning have been identified for the study area, and data on their spatial extents were obtained from a variety of sources as described in Table 1. Constraints include uses/users such as salmon farming areas, MPAs, commercial shipping, and areas unsuitable for aquaculture due to legal restrictions. Four data sets were used in the first stage of the site selection approach (Fig. 1) to acquire georeferenced historical information on the relevant constraints that can affect site suitability for Pacific oyster longline culture in the estuary (Table 1). Locations of licensed salmon aquaculture sites within the estuary were obtained from the Undersecretariat for Fisheries of Chile with information from April 2010 (SUBPESCA, 2010). Polygon vectors of salmon farm sites were converted to the base map raster format using a GIS overlay process. Georeferenced data on the location of MPAs, namely Management and Exploitation Areas for Benthic Resources (MEABR), were obtained from the Undersecretariat for Fisheries of Chile using information from March 2010 (SUBPESCA, 2009). Polygon vectors of MEABR sites were converted to a thematic image using the base map raster format. Spatial information on commercial shipping operations in the Valdivia estuary was obtained from the Chilean Navy's Hydrographic and Oceanographic Service electronic nautical chart N°6251 (SHOA, 1996). The electronic chart was imported and georeferenced in GIS, the shipping polygons were digitized and converted to a thematic image using the base map format. Geographic data on legal

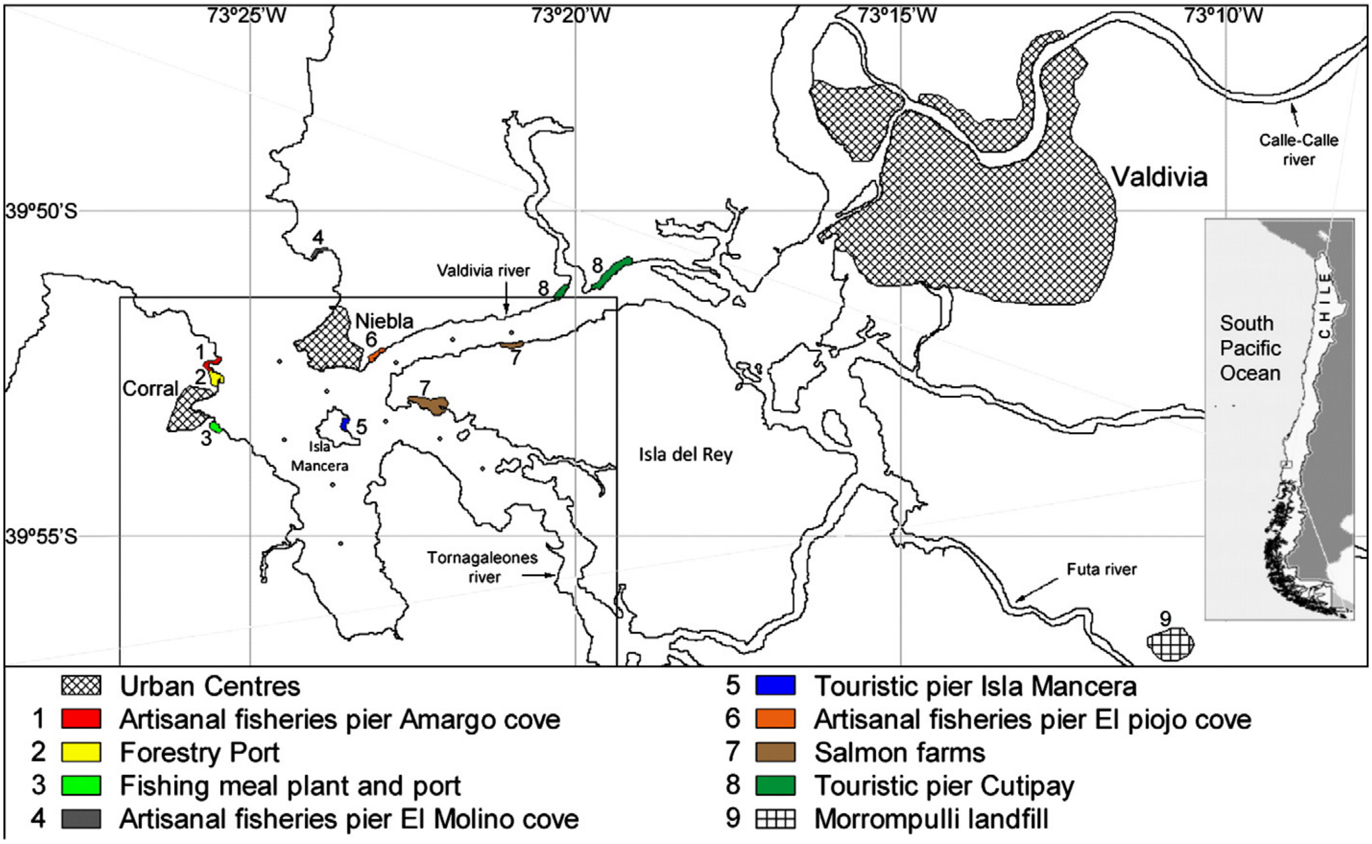

Fig. 2. Location of Valdivia estuary in south central Chile. The map shows the main land uses. The black frame indicates the study area and location of sampling points.

constraints related to unsuitable aquaculture areas were obtained from the Supreme Decree No. 792/1992 of the Ministry of Economy, Development, and Reconstruction which declared suitable areas for aquaculture in the Corral Bay and Valdivia River waterway sector (MINECON, 1992). Polygon vectors of UAA were generated and converted to an image using the base map format. Finally, the thematic maps for each constraint were reclassified to unsuitable or suitable areas and overlayed to produce a final social constraints image that defines suitable areas.

2.1.3. Stage 2: suitability for Pacific oyster aquaculture using Multi-Criteria Evaluation

In the second stage an MCE analysis is applied considering the criteria (sediment quality, water quality and ecological quality) that define suitability and their constituent factors (Fig. 1). The space factors and constraints are provided by the geography, marine spatial planning mechanism (regulatory constraints, sediment, water and ecological quality guidelines, areas of importance of wild fisheries, marine protected areas and navigation concerns) and requirements for marine farm development (bathymetry, water quality for growth and survival, hydrodynamics, etc.) (Inglis et al., 2000; McKindsey et al., 2006).

2.1.3.1. Factors influencing suitability for shellfish aquaculture. This analysis uses the influence of physical suitability, growth and survival, product quality, and environmental sensitivity for identification and classification of suitable shellfish areas (Fig. 1).

2.1.3.1.1. Physical suitability factors. The factors chosen were: water circulation, bathymetry and sediment type. Water circulation is known to be beneficial to shellfish culture in the supply of dissolved oxygen, food particles and dissipation of waste products (Vincenzi et al., 2006), while slack water and strong currents or wave action have detrimental effects (Dame and Prins, 1998). Additionally, excessive current increases drag on ropes, lines, trays, or other structures of aquaculture systems. The bathymetry of a site determines the type of culture system and the potentially cultured organisms. Depth, in conjunction with turbidity and light, may affect chlorophyll concentrations i.e. the amount of food available to a cultured organism at any given depth. Shellfish may be cultured at depths between 4 and 25 m (Longdill et al., 2007; Thomson, 1996). Sediment type plays a key role in defining the magnitude of potential impacts of shellfish aquaculture at a site (Longdill et al., 2007). Biodepositional impacts from a shellfish aquaculture site will depend in part on the existing habitat or sediment type, e.g. a rocky reef community will be more affected than a soft sediment community which will be able to break down deposited material more efficiently and effectively than areas lacking a range of benthic organisms (Mitchell, 2006). Soft sediment habitats, comprised of fine silty and muddy sediments with low organic content, are determined to be the most suitable benthic environments above which to site suspended shellfish aquaculture (Longdill et al., 2007).

2.1.3.1.2. Growth and survival factors. The factors chosen were: water temperature (Kobayashi et al., 1997; Roland and Brown, 1990; Van der Veer et al., 2006), food concentration (Barillé et al., 1997; Gangnery et al., 2003; Kobayashi et al., 1997; Roland and Brown, 1990) and salinity (Kobayashi et al., 1997; Mann et al., 1991). Water temperature (T) and available food in terms of chlorophyll *a* (Chl *a*) and particulate organic matter (POM), have an interacting effect upon assimilation efficiency in shellfish filters (Barillé et al., 1997; Gangnery et al., 2003; Roland and Brown, 1990). High temperatures can negatively affect growth during periods of low food availability and positively affect growth when combined with elevated levels of food

Table 1
Variables, data range values, data sources, measurements method, sampling depths, criteria, factor suitable range, FSR value and FSR source of data sets used in the suitability analysis of the Valdivia estuary for site selection of Pacific oyster aquaculture.

Variable	Maps data range	Data source	Measurement method	Sampling depths (m)	Criteria	Suitable range	FSR value	FSR source
Factors of growth and survival								
T (°C)	10–16.6	1	CTD*	1, 5, 10 and 15	WQ	8–34	1	9, 10, 11
						<8 and >34	0	
S (psu)	1–33.7	1	CTD*	1, 5, 10 and 15	WQ	10–35	1	10, 12
						<10 and >35	0	
TPM (mg L^{-1})	0.15–195	1	Loss on ignition	1 and 5	WQ	1–160	1	9, 10, 13
						<1 and >160	0	
DO (mg L^{-1})	3.8–5.9	1	Winkler	1 and 5	WQ	>4	1	14
						<4	0	
Chl *a* (μg L^{-1})	0.9–6.8	1	Spectrophotometer	0.5 and 5	WQ	1–55	1	9, 10, 13, 15
						<1 and >55	0	
POM (mg L^{-1})	0.07–16.7	1	Loss on ignition	1 and 5	WQ	1–55	1	9, 10, 13, 15
						<1 and >55	0	
Factors of physical suitability								
Currents speeds (m s^{-1})	0.29–0.89	1	Gytre SD current meter	0.5 and 8	WQ	0.1–2	1	17
						<0.1 and >2	0	
Bathymetry (m)	0.1–17.5	1	Single beam echosounder	n/a	WQ	4–25	1	18
						<4 and >25	0	
Sediment type (phi)	1.1–4.2	1	Van Veen grab and sieves	n/a	SQ	>0	1	18
						−8–0	0	
Factors of product quality								
Fecal coliform (coliform 100 ml^{-1})	167–302	2	Fermentation technique	0.5	WQ	<1000	1	16
						>1000	0	
As (μg g^{-1})	4.1–8.7	3	Hybrid generator	n/a	SQ	<33	1	19
						>33	0	
Cr (μg g^{-1})	17.1–26	3	FAAS**	n/a	SQ	<80	1	19
						>80	0	
Cu (μg g^{-1})	23–29.8	3	FAAS**	n/a	SQ	<70	1	19
						>70	0	
Fe (μg g^{-1})	29,008–38,896	3	FAAS**	n/a	SQ	<220,000	1	20
						>220,000	0	
Mn (μg g^{-1})	194.7–274.2	3	FAAS**	n/a	SQ	<260	1	20
						>260	0	
Pb (μg g^{-1})	4.9–10.1	3	FAAS**	n/a	SQ	<35	1	19
						>35	0	
PAHs (ng L^{-1})	74.7–214.5	4	UNEP/IOC/IAEA (1992)	n/a	SQ	<4022	1	19
						>4022	0	
TOM (%)	1.2–11.3	1	Loss on ignition	n/a	SQ	<5	1	18
						>5	0	
Factor of environmental sensitivity								
H′	0.54–2.02	1	Taxonomic identification		EQ	>3	1	21
						<3	0	
Regulatory and social constraints								
Salmon farms	n/a	5				n/a	0	
Legal unsuitable zones	n/a	6				n/a	0	
Commercial shipping	n/a	7				n/a	0	
MEABR	n/a	8				n/a	0	

1: Arcos et al. (2002); 2: Ramírez (2003); 3: Velázquez (2005); 4: Palma-Fleming et al. (2004); 5: SUBPESCA (2010); 6: MINECON (1992); 7: SHOA (1996); 8: SUBPESCA (2009); 9: Roland and Brown (1990); 10: Kobayashi et al. (1997); 11: Van der Veer et al. (2006); 12: Mann et al. (1991); 13: Barillé et al. (1997); 14: Vaquer-Sunyer and Duarte (2008); 15: Gangnery et al. (2003); 16: CONAMA (2004); 17: Vincenzi et al. (2006); 18: Longdill et al. (2007); 19: Long and Morgan (1990); 20: Department of Ecology (1995); 21: Labrune et al. (2006); n/a: Not applicable; FSR: factor suitability range; WQ: Water quality; SQ: Sediment quality; EQ: Ecological quality; *: Conductivity Temperature Depth sensor, **: Flame Atomic Absorption Spectrometry.

supply (Kobayashi et al., 1997). At temperatures lower than 8 °C, growth is significantly reduced or absent (Kobayashi et al., 1997). Available food, expressed either as POM or phytoplankton biomass (Chl *a*) follows the functional relationship between food concentration and assimilation efficiency in shellfish (Barillé et al., 1997). Water salinity (S) affects production of shellfish; values lower than 10 ppm and higher than 35 ppm may affect growth and survival (Kobayashi et al., 1997; Mann et al., 1991). Total particulate matter (TPM) and dissolved oxygen (DO) are additional environmental factors that may have an effect upon growth and survival. TPM concentrations in excess of 195 mg L^{-1} could be harmful to the shellfish and affect the filter feeding rate (Barillé et al., 1997; Kobayashi et al., 1997; Roland and Brown, 1990). DO is needed for shellfish respiration, and sublethal levels (<4 mg L^{-1}) can cause declines in feeding and growth (Vaquer-Sunyer and Duarte, 2008).

2.1.3.1.3. Product quality factors. The factors chosen were: fecal coliforms in water, and metals, polycyclic aromatic hydrocarbons (PAHs) and total organic matter (TOM) in sediment. High concentrations (>1000 coliform 100 ml^{-1}) of fecal coliforms in marine waters of shellfish harvesting areas affect shellfish quality. Additionally, they are a major human health risk and can indicate pathogenic diseases such as dysentery, typhoid fever, viral and bacterial gastroenteritis and hepatitis (CONAMA, 2004). Additionally, the pollution of metals (Department of Ecology, 1995; Long and Morgan, 1990; Persaud et al., 1989) and organic xenobiotics such as PAHs (Long and Morgan, 1990) are identified as environmental factors that influence the product quality of shellfish aquaculture. Several sediment quality guidelines developed to date for the protection of the aquatic environment are based on inorganic and organic chemical contaminant concentrations. TOM in sediment is identified as another important factor in assessing the potential impacts of shellfish culture on the product quality.

2.1.3.1.4. Environmental sensitivity factors. Shellfish leases may not be granted in or near some environmentally sensitive areas e.g. national parks, mangroves, wetlands and areas with high benthic biodiversity, which would potentially be compromised by organic enrichment (Pearson and Stanley, 1979). Castel et al. (1989) reported a reduction in the diversity of macrofauna from shellfish culture that was attributed to sediment anoxia. The protection of diversity of benthic fauna is an important factor to take into account in shellfish site selection. Areas of high diversity of benthic macrofauna should be protected as environmentally sensitive zones. The Shannon diversity (H′) index is used as an indicator of benthic macrofauna and can be classified as one of five categories of ecological quality (EcoQ) status (Bad, Poor, Moderate, Good, and High) in order to assess the environmental status of marine and coastal waters (Labrune et al., 2006; Lu et al., 2008).

2.1.3.2. GIS multilayered database and site suitability modelling. Information on the environmental conditions to be incorporated into a GIS database (Inglis et al., 2000) is required in order to assess the site suitability of a coastal area. Available information on the study area for each variable or factor must be identified using literature, thematic maps and statistics as data sources to build up a GIS multi-layered database. MCE techniques are used to aggregate contributing factors into a spatially variable (*x* and *y* co-ordinates belonging to the study area) Suitability ($S_{(x,y)}$) using GIS functions. MCE is used to combine the spatial factors (physical, growth and survival, product quality and environmental sensitivity) and social constraint images that influence the suitability for shellfish aquaculture in order to generate a final suitability map. The $S_{(x,y)}$ is calculated as the geometric mean of all factors, modified by their factor suitability range (FSR) which converts the original data to standardized aquaculture suitability scores (Arnold et al., 2000; Vincenzi et al., 2006), and subsequent restriction by the constraints (Eq. (1)).

$$S_{(x,y)} = \prod_{i=1}^{n} FSR_{(x,y,i)} \text{ where } C_{(x,y)} = 1 \text{ and } S_{(x,y)} = 0 \text{ where } C_{(x,y)} = 0 \tag{1}$$

Where $FSR_{(x,y,i)}$ is the spatially variable factor modified by its FSR into suitability levels; $i = 1....19$ is an index identifying the corresponding input parameters; and $C_{(x,y)}$ is the spatially variable constraints image. $S_{(x,y)}$ is a binary value which can be 0 (unsuitable) or 1 (suitable). Water quality and food availability FSR can be obtained from scientific literature on physiology and growth of cultured shellfish. Sediment quality FSR can be obtained from available sediment quality criteria guidelines. A weighted geometric mean can also be applied (Silva et al., 1999; Vincenzi et al., 2006), where each factor is assigned a weight to indicate relative importance, often determined subjectively by experts. However, Aguilar-Manjarrez (1996) has shown with specific reference to aquaculture that experts with similar backgrounds may not be consistent in the assignment of weights or ranking of importance. Different backgrounds bring differing opinions, resulting in a range of outcomes (Levings et al., 1995; Longdill et al., 2007; Nath et al., 2000). As a result, and to maintain generality and objectivity for the present methodology, no variable weightings are applied and the un-weighted geometric mean is used (Longdill et al., 2007). The final suitability map distribution is related to physical space available within the study area which limits the number and size of shellfish farms that can be developed.

2.1.3.3. Suitability for Pacific oyster aquaculture in the Valdivia estuary using Multi-Criteria Evaluation analysis

2.1.3.3.1. Data sources. Chile is a developing country with marine environments characterized by limited data availability. Four data sets from the study area were used in the second stage of the site selection approach (Fig. 1) to acquire historical spatial information on the relevant variables. All data are point vectors from field samples (Fig. 2). Data sources for each variable in conjunction with data range values, measurement methods and sampling depths used are summarized in Table 1. Mean values of vertical distribution of each variable were estimated for each sampling station. Seasonal data of T, S, DO, Chl *a*, TPM and POM were collected together with non-seasonal data (currents, bathymetry, sediment type, fecal coliforms, As, Cr, Cu, Fe, Mn, Pb, PAHs, TOM and H′).

Pacific oyster aquaculture suitability was estimated in the Valdivia estuary using an MCE analysis considering criteria (water quality, sediment quality, ecological quality) and a multi-layer of factors (physical suitability, growth and survival, product quality and environmental sensitivity) and social constraints (Fig. 1).

2.1.3.3.2. Factors influencing suitability. Water circulation and currents, bathymetry of the site and sediment grain size were the main factors identified as influencing the physical suitability for Pacific oyster aquaculture in the study site (Table 1). FSR for current speeds, bathymetry and sediment grain size were identified, considering the bibliographic sources (Table 1). Temperature, food concentration and salinity were the main factors identified as influencing the growth and survival of Pacific oyster in the study area (Table 1). Suitability ranges for T, S, TPM, DO, Chl *a* and POM were identified considering the bibliographic review of water quality criteria for growth and survival. Fecal coliforms in water and metals, PAHs and TOM in sediment were the factors identified as influencing the product quality of Pacific oyster in the study area (Table 1). Suitability ranges for fecal coliforms, metals (As, Cr, Cu, Fe, Mn and Pb), PAHs and TOM were identified by means of a bibliographic review of water quality and sediment quality criteria. The diversity of benthic macrofauna was identified as a factor influencing the protection of environmental sensitivity zones for Pacific oyster aquaculture in the study area (Table 1). A factor suitability range for the Shannon diversity index was identified using ecological quality criteria from the literature.

2.1.3.3.3. Base map, data interpolation and multi-layer generation. The generation of thematic maps and site-suitability analysis of farms in the geographic area selected in the Valdivia estuary was implemented using the IDRISI Andes™ GIS software (Fig. 1). The base map was digitized and compiled from a 1:30,000 Chilean National Topographic Institute chart. The base map generated had a spatial resolution of 37 × 37 m and represents a grid of about 110,000 cells for the study area (73°19′21″–73°27′W; 38°51′18″–39°57′S). Coastline vector and land mask were made to delimit the study area. Point sample data for each factor have been interpolated by means of the kriging algorithm over a grid with the same dimensions as the base map. The GSTAT™ geostatistical modelling software, available in IDRISI GIS, was used to produce a multi-layer database of the Valdivia estuary. Polygon and chart data were imported to GIS and converted to raster images with the same resolution as the base map.

2.1.3.3.4. Identification of suitable areas. As described in Section 2.1.2 and in this section, 4 constraints and 19 factors potentially affect Pacific oyster aquaculture site suitability for longline culture in the Valdivia estuary (Table 1). The multi-layers of factors were mapped using GIS functions and converted to suitability scores (0 or 1) considering the FSR and using GIS reclassification functions. A final suitability ($S_{(x,y)}$) map was generated using a MCE of factors suitability and constraints.

2.1.4. Stage 3: dynamic modelling at selected sites

In the third stage, a detailed analysis of production, socio-economic outputs, and environmental effects was applied by means of a farm-scale carrying capacity model using environmental drivers from areas previously identified as suitable (Fig. 1). The potential production carrying capacity of an area refers to stocking density that allows the sustainable harvest of shellfish to be maximized, by determining the optimum long-term production that the area will support (Inglis et al., 2000). The FARM model was applied to the areas selected in the previous stages (Fig. 1) to assess the potential production, socio-economic profits and negative and positive environmental externalities.

The general characteristics and implementation of the FARM model have been described in Ferreira et al. (2007a), and the application to multiple systems and shellfish species in Ferreira et al. (2009a, 2009b), and will be only briefly reported here, with an emphasis on new model developments. The model simulates processes at the farm-scale by integrating a combination of physical and biogeochemical models, shellfish and finfish growth models, and screening models for determining optimal production, income and expenditure, biodeposition, eutrophication assessment, and nutrient emissions. The input requirements of the model may be divided into three groups: (i) time-series of drivers for environmental conditions such as water temperature and salinity, current speed, tidal regime, Chl *a*, POM, TPM and DO; (ii) data on farm dimensions and positioning, existence of fish cages, etc.; and (iii) cultivation practice (e.g. seed density, cultivation period and harvest weight). A range of shellfish and finfish individual growth models are available for simulation in FARM. In this work, we used the AquaShell™ model (Ferreira et al., 2010), validated for Pacific oyster using experimental growth curves determined by Möller et al. (2001) for the Valdivia estuary. Results showed a significant relationship ($p<0.01$) to measured growth (Ferreira et al., 2010). The individual model uses a net energy balance approach (e.g. Hoffmann et al., 1995; Kobayashi et al., 1997) and draws on functions published in the literature (Brigolin et al., 2009; Dame, 1972; Hoffmann et al., 1995; Kobayashi et al., 1997; Ren and Ross, 2001), representing key physiological processes, together with new formulations. AquaShell was developed with the following objectives: a) to simulate change in individual weight, expressed as tissue dry weight and scaled to total fresh weight (with shell) and to shell length; b) to integrate the relevant physical and biogeochemical components, i.e. allometry, TPM, temperature, and salinity, and to partition the phytoplankton and detrital food resources; and c) to provide environmental feedbacks for production of particulate organic waste (feces and pseudofeces) excretion of dissolved nitrogen, and consumption of DO. FARM integrates an adapted version of the ASSETS eutrophication screening model (Bricker et al., 2003), to evaluate the impacts of a shellfish farm using Chl *a* and DO concentrations as indicators (Ferreira et al., 2007a). These indicators are combined in a decision matrix for Eutrophication Condition (EC) (Bricker et al., 2003) and are used to derive the final classification grade of the State of the system (High, Good, Moderate, Poor or Bad) for each potential farm site, following the classification scheme of the EU Water Framework Directive (WFD) (see e.g. Ferreira et al., 2007c).

2.1.4.1. Application to selected sites. The model for Pacific oyster production was applied in those areas considered to be potentially suitable by the MCE GIS evaluation analysis by testing a specific farm layout, and using available environmental forcing data, under current conditions of production and operation in Chile. The shell length of Pacific oyster individuals, and the production and return on investment of the cultivated population, expressed as Total Physical Product (TPP), Average Physical Product (APP, output/input) and Marginal Physical Product (MPP, the first derivative of the TPP curve) were simulated at each farm site for a cultivation period of 13 months. The optimal production, income and expenditure in each suitable area were determined in the socio-economic analysis made with the FARM model. The role of Pacific oyster farms in biodeposition and in top-down eutrophication control through bioextraction was assessed in each selected area by means of the FARM model (Ferreira et al., 2007a). Two test sites in the Valdivia estuary were screened for suitability as potential oyster farming areas (Ferreira et al., 2010; Silva, 2009).

3. Results

Results for the components of the three-stage methodological approach are presented below.

3.1. Regulatory and social constraints analysis

Fig. 3 illustrates the spatial distribution of the suitable sites obtained in the social constraints analysis using GIS functions. The social constraints image limits the areas for Pacific oyster culture to about 17.5 km^2, 43% of the region under consideration. The social factors constraining the unsuitable areas include legally unsuitable aquaculture zones (18.1 km^2, 44.6% of total), commercial shipping zones (16.7 km^2, 40.9%), salmon aquaculture farms (0.29 km^2, 0.71%) and MEABR protected areas (0.11 km^2, 0.28%).

3.2. Suitability of Pacific oyster culture using Multi-Criteria Evaluation

Final output spatial distributions of the multi-layers of factors (physical, growth and survival, product quality and environmental sensitivity) generated using GIS interpolation functions are shown in Fig. 4. Seasonal and spatial variability are observed in the water quality factors (Fig. 4a). Higher food (Chl *a* and detrital POM) and DO available in Tornagaleones river and in the marine area of Valdivia river, suggest that they are the most productive regions within the estuary. Higher concentrations of POM, TPM, and freshwater are transported to the estuary by the Valdivia River. High spatial variability is observed in the physical factors (Fig. 4b). Sediment type varies from medium sand in the Valdivia River to silty in the south of Isla Mancera, which is appropriate for suspended shellfish culture. The depth reaches a maximum of 18 m at the mouth of the estuary, and shallower (<4 m) regions, which restricted the suitable areas to the south of Isla Mancera and in coastal areas of the Tornagaleones and Valdivia Rivers. Current speed is suitable for

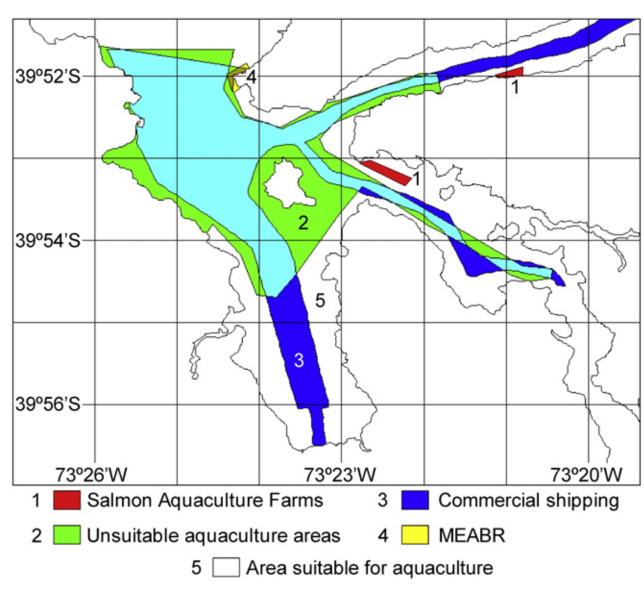

Fig. 3. Regulatory and social constraints to the zoning of GIS suitable sites within the study area in the Valdivia estuary. See Table 1 for sources of data sets used as constraints. The large (turquoise) area within area 2 is the overlay between areas 2 and 3.

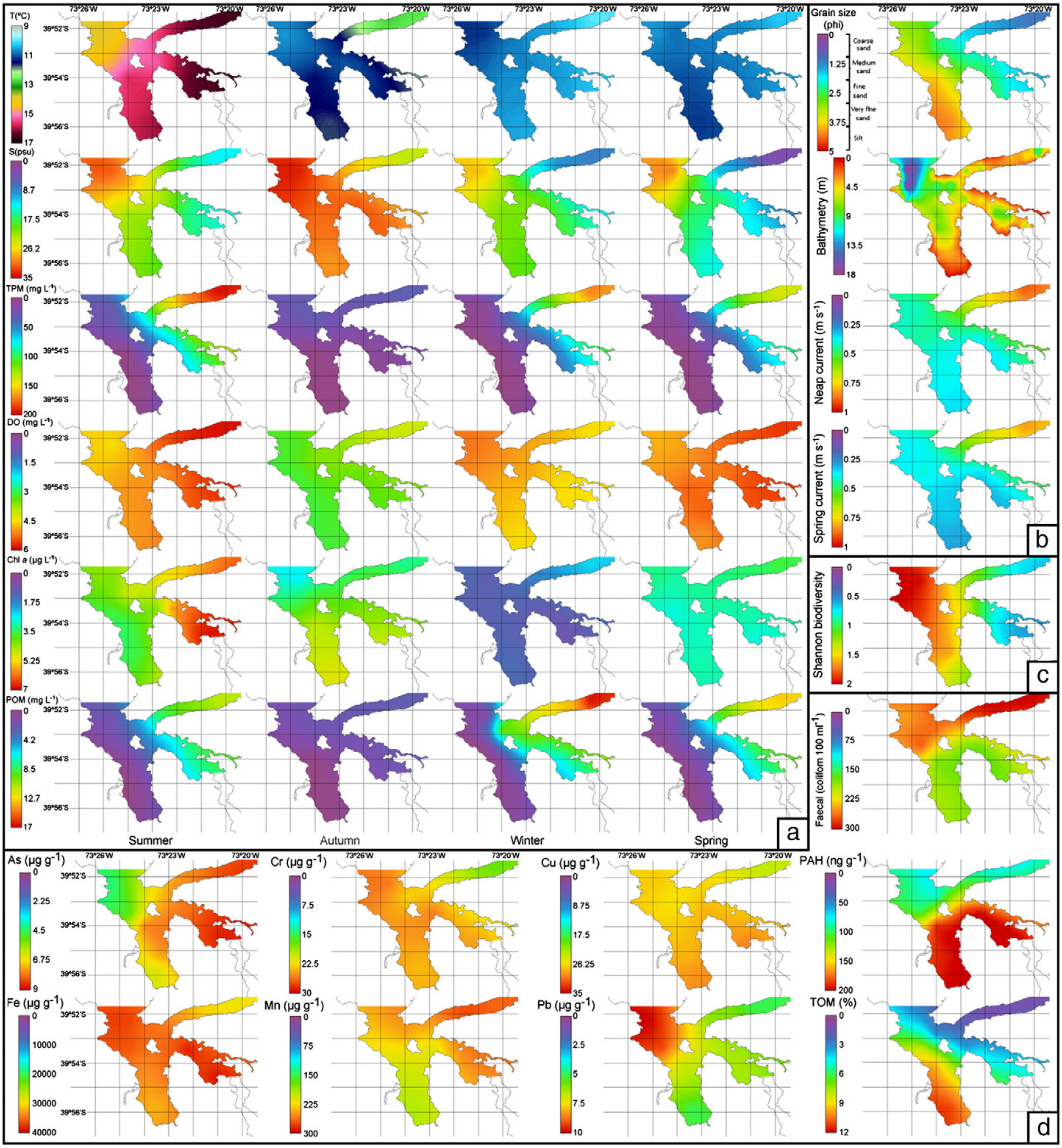

Fig. 4. Multi-layers of: a) seasonal water quality factors that influence oyster growth and survival; b) factors of physical suitability; c) factors of environmental sensitivity; and d) factors of product quality.

shellfish culture, with higher values observed in the Valdivia River. The highest biodiversity of benthic macrofauna is found in areas near the mouth of the estuary where there is a greater influence of seawater, while low values are found in areas influenced by freshwater (Fig. 4c). High spatial variability of metal concentrations in sediments is observed in the estuary, mainly associated with freshwater input from Valdivia River and seawater influences (Fig. 4d). High values of Mn observed in sediments of the Valdivia River place it outside of the acceptable limits for shellfish culture. Higher fecal coliform concentration is observed in the Valdivia River (Fig. 4d) due to effluent discharges to the river from urban areas, mainly in Valdivia city (Fig. 2). Higher PAH values in sediments are observed at the south of Isla Mancera and in Tornagaleones River, while higher organic matter in sediments is related to very fine sand and silty areas at south of Isla Mancera (Fig. 4d).

Fig. 5 summarizes the MCE approach and the results obtained. Spatial distribution results of regulatory and social constraints obtained in Stage 1 were considered (Fig. 5a). Results for physical suitability showed that suitable areas were constrained by the bathymetry of the area, while the grain size and water current speeds are always within acceptable limits for Pacific oyster culture. Suitable areas according to the physical criteria suggest that 26.3 km^2, 64.8% of the study area (Fig. 5b), are available. Results of the screening analysis for water quality (T, S, TPM and DO) and food availability (Chl *a* and POM) factors that influence oyster growth and survival, might account for 14 km^2, 34.3% of the study area (Fig. 5c). Suitable areas cover a large part of Tornagaleones River, Isla Mancera, Niebla coast and one third of the Valdivia River. Water quality and food availability factors show a spatio-temporal variability (Fig. 4) that influences the suitability (Fig. 5c). Temperature is always within acceptable limits for Pacific oyster. Salinity varies widely; unsuitability was restricted to areas with values below 10 psu located in the east part of the Valdivia River during winter and spring. Turbidity is higher in the Valdivia River during winter and summer and this factor also constraints the areas suitable to oyster survival.

Low DO concentrations during autumn also reflect an unsuitable area in the coastal zone of Corral and west and southwest part of Isla Mancera. The amount of food available also limits the area; unsuitable sites were represented by low concentrations of Chl *a* during winter in the south coast of Tornagaleones River and low values of total POM all year round in the Corral coast and south and southern and western parts of Isla Mancera.

Suitable areas related to product quality factors were restricted by high concentrations of Mn and TOM in sediments, while other variables (fecal coliforms, As, Cr, Cu, Fe, Pb and PAHs) are within acceptable ranges according to water and sediment quality criteria. Suitable areas based on product quality factors corresponded to 17 km^2, 41.9% of the total region (Fig. 5d). The Shannon biodiversity of benthic macrofauna, used as the environmental sensitivity factor, is within acceptable ranges for ecological quality criteria and all the study area is screened as suitable (Fig. 5e).

For a total of 19 factors and 4 constraints, the final output from the multi-criteria suitability analysis indicates that 3 km^2 (7.6%) of the survey region is suitable for Pacific oyster culture (Fig. 5f).

3.3. Site selection

Four sites from the areas found to be suitable (Niebla, Valdivia, Isla del Rey, and Tornagaleones) were used in a detailed analysis of production, socio-economic outputs and environmental effects using the FARM carrying capacity model (Fig. 5f). The main characteristics of environmental data extracted at each suitable site from the multi-layer factors and used to drive the FARM model are shown in Table 2.

Production results obtained for the potential sites show significant differences at a standard seed density of 100 ind. m^{-2}, considering a test farm area of 6 ha, a culture period of 395 days, a seed weight of 1.2 g, a harvest weight of 90 g, and a natural mortality of 0.35 y^{-1} (Table 3). The Tornagaleones site showed the highest production, with a TPP of 139.6 t TFW and an APP of 11.64 after the cultivation period. At the Valdivia site, a TPP of 75.5 t TFW and an APP of 6.3 was estimated, while the Niebla area only reached a production of 18.9 ton TFW and an APP of 1.57. These results suggest that Tornagaleones is the most promising site for Pacific oyster culture; the Valdivia and Isla del Rey sites are satisfactory; and Niebla area is less interesting and marginal. The model outputs for a standard seed density simulation suggest that the Tornagaleones site is a promising area for oyster cultivation, with fast growth and a good return on investment, as shown by the APP and by the predicted income.

Socio-economic outputs from the marginal analysis of the optimal profit for each farm site and a comparison with the standard seed density farming are shown in Table 3. The optimal profit for the Tornagaleones site occurs at seeding densities of about 210 t and the resulting TPP was estimated to be 952.5 t, with a harvest profit of about 4552 k€. At the optimal point the APP = 4.54, indicating that harvestable biomass is over 4× the seed biomass. Valdivia shows moderate optimal profit with APP of 2.47, followed by Isla del Rey with a low value (APP = 1.85) and Niebla, very low (APP = 0.77). Of

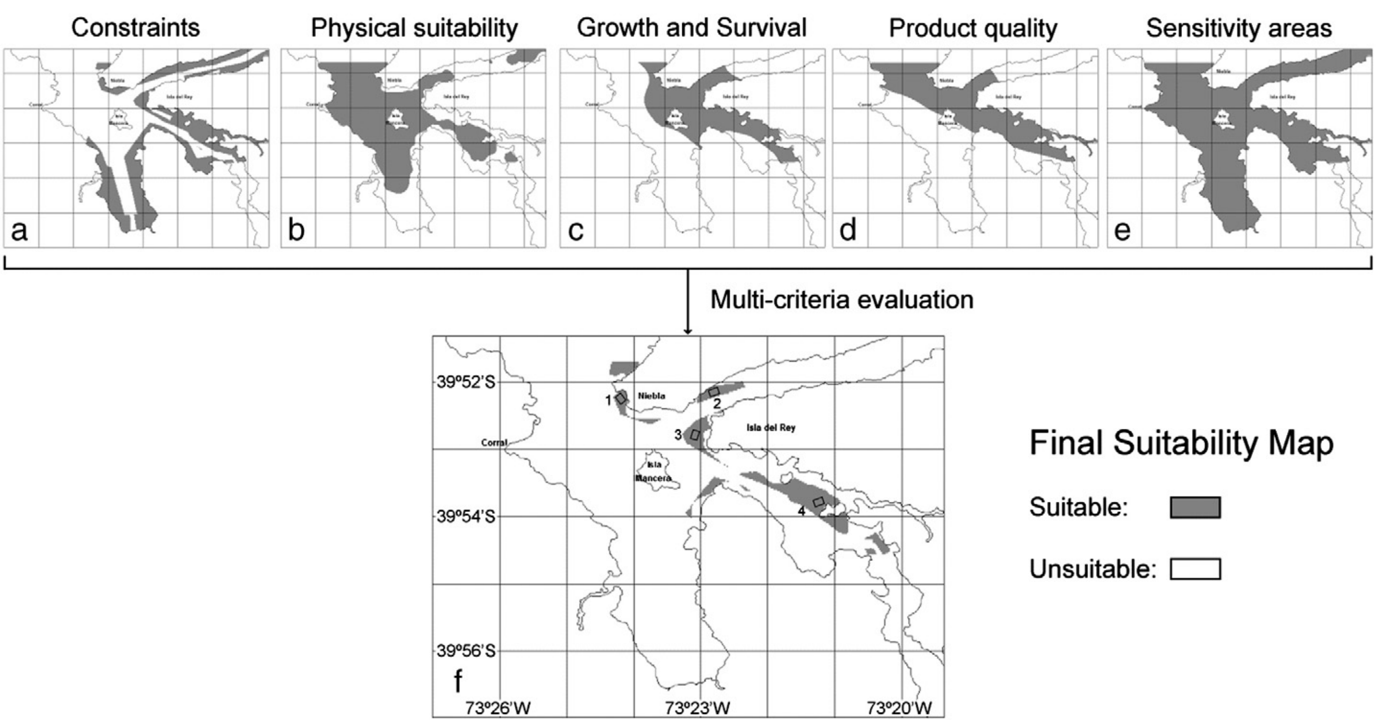

Fig. 5. Suitability maps according to criteria of a) regulatory and social constraints; b) physical suitability; c) growth and survival; d) product quality; e) environmental sensitivity areas; and f) final suitability map derived from the Multi-Criteria Evaluation. The final suitability map also showed the four selected areas to be assessed the carrying capacity: 1) Niebla, 2) Valdivia, 3) Isla del Rey and 4) Tornagaleones.

Table 2
Main environmental characteristics of the four suitable sites.

Variable	Niebla	Valdivia	Isla del Rey	Tornagaleones
T (°C)	10.7–14.1	10.4–16.3	10.7–15.4	10.6–16.3
S (psu)	27.1–33.7	10.8–27.9	14.8–29.8	13–31.1
Chl *a* ($\mu g\ L^{-1}$)	1–4.1	2.0–5.5	1.4–4.7	0.9–6.2
POM ($mg\ L^{-1}$)	1.2–3.4	2.4–6.6	2.1–10.5	3.6–5.1
TPM ($mg\ L^{-1}$)	3.7–19.9	9.8–43.6	22.4–86.6	8.4–26.7
DO ($mg\ L^{-1}$)	3.2–5.2	4.1–5.7	4.3–5.2	4.1–5.4

the four potential farm sites evaluated, Tornagaleones would be the most successful with respect to profitability.

Environmental impact results of FARM modelling for standard seed density and optimized density for Pacific oyster farms in the Valdivia estuary are shown in Table 4, including only the productive (suitable growth, profit and APP) areas of Tornagaleones and Valdivia, while the Niebla and Isla del Rey sites are of marginal interest and thus rejected for further biodeposition and eutrophication analysis. Pacific oyster farms generate biodeposits as a negative environmental impact, although organically extractive culture by definition lowers the concentration of suspended organic particles in the water column, leading to a net reduction in phytoplankton and detritus. Results of biodeposition simulated by FARM are shown in Table 4 for the two potential Pacific oyster farms. Areas where oyster cultivation is successful are characterized by an adequate food supply. As an example, the natural sedimentation at Tornagaleones prior to shellfish stocking would lead to a gross deposition of about 7.43 $kg\ m^{-2}\ y^{-1}$ of particulate organic carbon (POC), and an equivalent sediment accretion rate of 7.52 $mm\ y^{-1}$. At the simulated stocking densities, the farm footprint corresponds to about 7.64 $kg\ m^{-2}\ y^{-1}$ POC, with a slightly higher accretion rate of 7.73 $mm\ y^{-1}$. FARM does not account for vertical turbulence, sediment erosion or diagenesis, and thus provides a precautionary estimate of biodeposition. The effective rate of sediment organic enrichment due to cultivation is a low value of approximately 0.1%, considering no mitigating factors. Table 4 shows the component of this mass balance derived from biodeposits produced by the Pacific oyster, under the assumption that all those deposits reach the benthic layer. As referred above, the biodeposits *per se* must be a smaller input than the organic sedimentation in an unstocked area, because the organic particles are being removed as a food source.

FARM model results showing positive environmental impacts are obtained from a carbon and nitrogen mass balance, based on

Table 3
Comparison of standard seed density situation and profit maximization scenarios for the four farm sites evaluated.

	Niebla	Valdivia	Isla del Rey	Tornagaleones
Standard density				
Seed (t TFW)	12	12	12	12
TPP (t TFW)	18.9	75.5	47.1	139.6
APP	1.57	6.3	3.93	11.64
Harvest profit (k €)	82.5	365.7	223.6	686
PEQ y^{-1}	1094	1279	1164	1549
Harvest income (k € y^{-1})	87.3	349.0	217.7	645.2
Total income (k € y^{-1})	120.1	387.4	252.7	691.7
Profit maximization				
Seed (t TFW)	108	147	66	210
TPP (t TFW)	83.1	363.8	121.8	952.5
APP	0.77	2.47	1.85	4.54
Harvest profit (k €)	307	1672	543	4552
PEQ y^{-1}	8837	12,910	5820	22,015
Harvest income (k € y^{-1})	383.9	1680.9	562.9	4400.6
Total income (k € y^{-1})	649.0	2068.2	737.5	5061.0

Table 4
Environmental impacts outputs of FARM model for standard seed density (100 ind. m^{-2}) and optimization analysis at the two potential Pacific oyster farms in the estuary of Valdivia: Valdivia (V) and Tornagaleones (TG).

Variable	V site	V site optimized	TG site	TG site optimized
Environmental impact				
Deposition of POC ($kg\ m^{-2}\ y^{-1}$)	7.58	9.15	7.64	10.44
Sediment organic enrichment (% POC y^{-1})	6.83	8.04	6.88	9.03
Sediment accretion rate ($mm\ y^{-1}$)	7.67	9.26	7.73	10.57
Carbon removal ($kg\ C\ y^{-1}$)				
Phytoplankton removal	−7112	−67,788	−8860	−117,015
Detritus removal	−49,659	−507,091	−60,000	−866,008
Nitrogen removal ($kg\ N\ y^{-1}$)				
Phytoplankton	−1106	−10,545	−1378	−18,202
Detritus	−7725	−78,881	−9333	−134,712
Excretion	466	4665	576	8129
Feces	4084	41,549	4942	70,997
Mortality	62	609	81	1138
Mass balance	−4220	−42,602	−5111	−72,651
Population equivalents (PEQ y^{-1})	1279	12,910	1549	22,015
ASSETS score inflow	Moderate	Moderate	Moderate	Moderate
ASSETS score outflow	Good	Good	Moderate	Good
Income				
Shellfish farming (k € y^{-1})	349.0	1680.9	645.2	4400.6
Nitrogen removal (k € y^{-1})	38.4	387.3	46.5	660.5
Total (k € y^{-1})	387.4	2068.2	691.7	5061.0

depletion of these elements through ingestion of phytoplankton and detrital organic material by oyster filtration and return of these through excretion and elimination (Table 4). At standard and optimized densities the Tornagaleones site showed highest C removal values and Valdivia lowest in the standard scenario, with 69 t Cy^{-1} and 57 t Cy^{-1} respectively. At standard and optimized densities, the Tornagaleones site showed the highest net nitrogen removal from the water through filtration of algae and detritus by oysters, with annualized net removals in the standard scenario of 5.1 t Ny^{-1} corresponding to a nitrogen input of 1549 population equivalents[1] per year (PEQ y^{-1}). The Valdivia site showed the lowest nitrogen removal, with annualized gross removal of 4.2 t N y^{-1}. The additional positive socio-economic impact obtained in the aggregate income due to both the shellfish sale and substitution value of land-based fertilizer reduction or nutrient treatment is shown in Table 4. At standard densities the Tornagaleones site showed the highest total (691.7 k€) income from shellfish sales (645.2 k€) and substitution cost of nutrient treatment (46.5 k€).

Results from the application of the ASSETS model implemented in FARM provide a eutrophication indicator at the local scale, and are examined for the two potential oyster farms (Table 4). The eutrophication indicator score shows that oyster farms have significant positive effects on water quality in the Valdivia site at standard and optimized seed densities, where the status improves from *Moderate* to *Good*. The quality status of the inflowing water at the Tornagaleones site is *Moderate*, both at standard and optimized densities, and there is no effect on outflowing water quality at standard density; at optimized seed density a significant positive impact is obtained with a status change from *Moderate* to *Good*. Positive changes in the ASSETS score are obtained in the Valdivia and Tornagaleones sites because Chl *a* concentration falls into the Low (<5 $\mu g\ L^{-1}$) eutrophication category due to high phytoplankton removal.

[1] Population equivalent (PEQ) is the load (e.g. of nitrogen or phosphorus) corresponding to the emissions of one person, irrespective of the origin of the load (e.g. direct human input, agriculture, livestock, or industry).

4. Discussion

The results regarding the development and testing of a three-stage approach for site selection for shellfish aquaculture suggest the usefulness of an integrated methodology of GIS and dynamic modelling tools to identify suitable areas and estimate potential production, socio-economic outputs, and environmental externalities.

The Valdivia estuary offers potentially suitable conditions for Pacific oyster culture development. However, consistent with other regions worldwide (Halide et al., 2009; Longdill et al., 2008; Pérez et al., 2005; Radiarta et al., 2008), existing multiple users and uses of the coastal environment severely restrict potential sites where aquaculture development can take place with minimal mediation between conflicting user groups. Other important social constraints such as potential users/uses of coastal area (i.e. water sports, species conservation, coastal recreation, distance to land-based facilities, sewage pipes, anchorages, cultural sites, among others) should also be considered in order to integrate all the conflicting uses under the coastal zone management scheme. Ideally, the interests of all stakeholders need to be addressed within an integrated coastal zone management (ICZM) plan, in order to assess the social carrying capacity of the aquaculture management area (McKindsey et al., 2006).

The FARM model results obtained for carbon and nitrogen mass balance showed the positive environmental impacts generated at the suitable sites by the high net nitrogen removal from the water through filtration of algae and detritus by shellfish (Table 4). The net removal of carbon and nitrogen has a direct relevance to integrated coastal zone management (Ferreira et al., 2007a; Ferreira et al., 2009a, 2009b).

Shellfish culture can help reduce eutrophication symptoms by removing chlorophyll, thereby increasing water clarity, which promotes growth of submerged aquatic vegetation and reduces the decomposition of organic material, which in turn reduces secondary eutrophication symptoms such as oxygen depletion (Bricker et al., 2003; Ferreira et al., 2007a; Ferreira et al., 2009a, 2009b). The components of eutrophication assessment, nutrient budget of shellfish farms (Brigolin et al., 2009; Ferreira et al., 2009a, 2009b), and the implementation of a nutrient credit trading in ICZM for aquaculture site selection are central to this approach.

The carbon mass balance is useful for examining the role of organic extractive aquaculture on the global carbon budget, but only from the perspective of filtration of algae and detritus and subsequent growth of shellfish tissue. A number of recent proposals for the use of fixation of CO_2 in bivalve shells as a mechanism for increasing carbon dioxide drawdown from the atmosphere fail to account for the simultaneous removal of calcium: the changes to seawater alkalinity lead to increased release of CO_2 to the water, resulting in a net atmospheric exchange of zero.

The nitrogen mass balance is of direct relevance to coastal management on a local scale, particularly for ICZM (Ferreira et al., 2007b, 2009a, 2009b; Lindahl and Kollberg, 2009; US EPA, 2001). There is increasing support (Ferreira et al., 2009a, 2009b; Lindahl and Kollberg, 2009) for a top-down approach for removal of nutrient-related eutrophication symptoms from the environment through shellfish (e.g. oyster) farming. This is seen as a competitive compensation measure for anthropogenic emissions to the coastal zone in a nutrient credit trading framework.

A pilot system is under preparation for the Baltic Sea (Lindahl, pers. com.) to explore this kind of low cost and environmentally effective nutrient removal option. Models and modelling systems of the kind illustrated here can support the study of policy alternatives that could effectively incorporate nutrient assimilation credits into national, regional or local nutrient reduction programs.

The biodeposition results indicate that the effective rate of sediment organic enrichment due to cultivation is low even when considering no mitigating factors at the two potential farm sites. As shown by Giles et al. (2009), factors such as turbulence and erosion greatly reduce the impact of biodeposition from shellfish farms, which in contrast to finfish operations (e.g. Weise et al., 2009), normally only show problems derived from poor regulation (e.g. inappropriate siting with respect to current speed) and/or poor culture practice (e.g. excessive stocking density). The excess biodeposition for the stocked farm is thus partly due to the biodeposit production by the animals and partly to the natural sedimentation of suspended particles as they are advected across the farm area. No significant impacts of shellfish farming on the benthos are identified, which agrees with the findings of other authors (e.g. Fabi et al., 2009), even in cases of highly developed shellfish culture (Zhang et al., 2009). The addition of a biodeposition component to the FARM model provides the missing element for an integrated analysis of the impacts of shellfish farming and to assess the ecological carrying capacity, which combines the valuation of the water quality aspects, with respect to the reduction of eutrophication symptoms, and the negative aspects of benthic organic enrichment.

Although GIS is useful as a marine spatial planning tool using MCE, the final suitability map is limited by some level of uncertainty in the application of FSR. However, the use of FSR is a necessity for the implementation of the MCE technique and for the integration of several data sets. At present there is no standardized set of criteria and suitability indicators for coastal aquaculture, although there is a need for their establishment and implementation (Frankic and Hershner, 2003; Kapetsky and Aguilar-Manjarrez, 2007). Nevertheless, it is expected that our integrative approach to shellfish aquaculture will be applicable in other parts of the Chilean coast, although scaling functions of FSR should be adjusted to environmental (physical and biogeochemical) site-specific factors.

The use of satellite data for aquaculture planning has been emphasized by many studies (Aguilar-Manjarrez et al., 2010; Kapetsky and Aguilar-Manjarrez, 2007; Longdill et al., 2008; Pérez et al., 2005; Radiarta et al., 2008; Rajitha et al., 2007). Remote sensing is an important and cost-effective approach for developing countries and data-poor regions. Improved methods for data access, particularly remotely sensed data, will contribute to the change of scattered data points into more meaningful information, especially in developing countries where there is a scarcity of *in situ* data measurements. In addition, it will promote a more informed decision-making process for coastal aquaculture management and the use of better data and more sophisticated virtual technology.

5. Conclusions

The methodological approach presented in this paper illustrates how GIS-based models (i.e. MCE) may be used in conjunction with other tools, such as a farm-scale carrying capacity model, to assist decision-makers in the practical application of an ecosystem approach to aquaculture (EAA) as proposed by FAO (Aguilar-Manjarrez et al., 2010; Soto et al., 2008).

This methodology for site selection addresses the concept of the four pillars (physical, production, ecological and social) of sustainable carrying capacity in aquaculture management (Inglis et al., 2000). The GIS-based stages (1 and 2) for identification of suitable areas through the exclusion of unsuitable ones are associated with the physical (e.g. suitable ranges of depths and current speeds), production (screening of food availability, xenobiotics, enteric microorganisms), ecological (e.g. protection of biodiversity, marketing of “green” products), and social pillars (e.g. legal constraints and multiple uses as marine protected areas, shipping and tourism). Stage 3 provides a detailed analysis of production carrying capacity (e.g. optimization of yield and profit), and ecological effects (e.g. biodeposition, eutrophication).

Rich data sets will improve confidence in the site selection approach outputs, but even in data-poor contexts, this kind of screening approach can support the licensing process, assist with farm financing, and help managers decide on acceptable environmental trade-offs. This integrative approach can be applied in data-poor countries with high aquaculture sector growth to improve environmental management. It can also be used to promote sustainable shellfish culture in conjunction with the cultivation of fed aquaculture species to create a balanced system (Chopin, 2006; Neori et al., 2004) for environmental sustainability (biomitigation), economic stability (product diversification and risk reduction), and social acceptability (better management practices).

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