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

C. Silva [a,b], J.G. Ferreira [c,*], S.B. Bricker [d], T.A. DelValls [e], M.L. Martín-Díaz [e], E. Yáñez [b]

[a] Cátedra UNESCO, Facultad de Ciencias del Mar y Ambientales, Polígono Río San Pedro s/n, 11510 Puerto Real, Cádiz, Spain
[b] Escuela de Ciencias del Mar, Pontificia Universidad Católica de Valparaíso, Avda. Altamirano 1480, Casilla 1020, Valparaíso, Chile
[c] Centre for Ocean and Environment, DCEA, FCT, Universidade Nova de Lisboa, Qta Torre, 2829-516 Monte de Caparica, Portugal
[d] NOAA — National Ocean Service, NCCOS, 1305 East West Highway, Silver Spring, MD 20910, USA
[e] Departamento Química Física, Facultad de Ciencias del Mar y Ambientales, Polígono Río San Pedro s/n, 11510 Puerto Real, Cádiz, Spain

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A B S T R A C T

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.

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).

* Corresponding author.
E-mail address: joao@hoomi.com (J.G. Ferreira).

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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