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Research Article

Using indicators and models for an ecosystem approach to fisheries and aquaculture management: the anchovy fishery and Pacific oyster culture in Chile: case studies

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ABSTRACT. This study illustrate the use of indicators and models to support the Ecosystem Approach to Fisheries and Aquaculture management using two case studies in Chile: prediction of environmental variability effects upon anchovy (*Engraulis ringens*) fishery of northern Chile and prediction of suitable sites and carrying capacity of Pacific oyster (*Crassostrea gigas*) culture using FARM and geographic information system (GIS) models in the Valdivia estuary. A three stage approach was applied: Stage 1 considers spatio-temporal ecosystem indicators (fisheries, aquaculture, environmental, and regulatory), Stage 2 uses statistical relationships between indicators, GIS, and other simulation models (*e.g.*, artificial neural networks and FARM) of environment-resources interaction, and Stage 3 is the analysis and validation of models outputs. The methodology illustrates how indicators and models may be used to assist decision-makers in developing an ecosystem approach to fisheries and aquaculture. The application of these approaches provides an integrative methodology for abundance prediction of anchovy and site selection for shellfish aquaculture, despite limitations in the available data.

Keywords: ecosystem approach, fisheries, aquaculture, GIS, PFG model, artificial neural network, carrying capacity.

Aplicación de indicadores y modelos para un enfoque ecosistémico de la pesca y la acuicultura: pesquería de anchoveta y cultivo de ostra del Pacífico en Chile: casos de estudio

RESUMEN. Este trabajo muestra el uso de indicadores y modelos para apoyar la aplicación del enfoque ecosistémico en la gestión de la pesca y la acuicultura, mediante dos casos de estudios en Chile: predicción de los efectos de la variabilidad ambiental en la pesquería de anchoveta (*Engraulis ringens*) en la zona norte de Chile y la predicción de sitios aptos y capacidad de carga para el cultivo de la ostra del Pacífico (*Crassostrea gigas*) en el estuario de Valdivia. Se aplicó un enfoque metodológico de tres etapas: etapa 1 considera indicadores espacio-temporales del ecosistema (pesca, acuicultura, medio ambiente y legislación); etapa 2 utiliza relaciones estadísticas entre los indicadores, funciones de SIG (Sistemas de Información Geográfica), y otros modelos de simulación (Redes Neuronales Artificiales y Capacidad de Carga) de interacciones entre el ambiente y los recursos; y etapa 3 es el análisis y validación de los resultados de los modelos. La metodología y resultados ilustran cómo los indicadores y modelos pueden ser utilizados para ayudar a los tomadores de decisiones en el desarrollo de un enfoque ecosistémico en pesca y acuicultura. La aplicación de estos enfoques ofrece una metodología integradora para la predicción de la abundancia de la anchoveta y la selección de sitios para el cultivo de moluscos, a pesar de las limitaciones de los datos disponibles.

Palabras clave: enfoque ecosistémico, pesquería, acuicultura, SIG, modelo PFG, redes neuronales artificiales, capacidad de carga.

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INTRODUCTION

Fisheries and aquaculture supplied the world with about 110 million tonnes of fish food in 2006 (~16.7 kg per capita), which is among the highest on record (FAO, 2009). Aquaculture accounted 47% of the fish food supplied and was the fastest growing food-producing sector. However, this strong expansion in the aquaculture industry has brought significant issues, including increased demands on fisheries for fish meal and fish oil (Delgado *et al.*, 2003; Diana, 2009), organic sediment enrichment and eutrophication (Holmer *et al*., 2005; Kalantzi & Karakassis, 2006), pharmaceuticals, organics, bactericidal and metal pollution (Cabello, 2006; Calvi *et al*., 2006; Sapkota *et al*., 2008), and changes in endemic populations biodiversity (Tomassetti & Porrello, 2005; Vezzulli *et al*., 2008). Additionally, the implications of fishing effort, environmental variability, and global climate change are major concerns for the sustainability of fisheries (FAO, 2008).

Nevertheless, fisheries and aquaculture decision makers can mitigate these potential impacts through the incorporation of an Ecosystem Approach to Fisheries (EAF) (García *et al*., 2003), and an Ecosystem Approach to Aquaculture (EAA) (FAO, 2006; Soto *et al*., 2008; Aguilar-Manjarrez *et al*., 2010), into integrated coastal zone management (ICZM) plans. An EAF management application includes prediction of environmental variability effects on fish stocks and fisheries (García *et al*., 2003). EAA management applications should include predictions of environmental variability effects on aquaculture, to estimate carrying capacity and identify suitable sites for farms (Aguilar-Manjarrez *et al*., 2010). The ecosystem should be taken into account when making predictions of the fisheries' abundance, suitable sites for aquaculture, potential aquaculture production and economic outputs to minimise environmental impacts and social conflicts, maximise economic returns (GESAMP, 2001; García *et al*., 2003), and ensure sustainable development (Kapetsky & Aguilar-Manjarrez, 2007).

Over the last decade, the research community has developed methodologies such as the geographic information system (GIS), and predictive models to support decision making for the EAF (Cochrane *et al*., 2007; Yáñez *et al*., 2008; Meaden, 2009) and EAA (Ferreira *et al*., 2007; Silva *et al*., 2011). However, there is a pressing need for such tools and methodologies to be more targeted at industry and management. Furthermore, the impacts of global climate change on the sustainability of fisheries and the environmental impacts caused by the great expansion of aquaculture are two major concerns. Therefore, it is important to develop and test frameworks that incorporate predictions of the environmental effects on fisheries (Jennings, 2005; Travers *et al*., 2007), aquaculture site suitability (Silva *et al*., 1999; Longdill *et al*., 2008), potential production, economic output, and environmental impacts (Ferreira *et al*., 2009; Silva *et al*., 2011).

GIS is one of the key tools in facilitating the development and administrative decisions of EAF and EAA management due to its ability to incorporate many diverse and complex spatio-temporal factors (Carocci *et al*., 2009; Aguilar-Manjarrez *et al*., 2010). Furthermore, GIS is a key tool for the development of new knowledge and for understanding the interactions between human activities (fisheries and aquaculture) and ecosystems (Soto *et al*., 2008; Carocci *et al*., 2009). Many authors have applied GIS modelling to fisheries (*e.g.,* Yáñez *et al*., 2004; Close *et al*., 2006; Meaden, 2009) and aquaculture planning (*e.g.*, Rajitha *et al*., 2007; Longdill *et al*., 2008; Radiarta *et al*., 2008).

The use of innovative virtual tools, such as ANN (Artificial Neural Networks), in EAF modelling, began in the last decade. In particular, non-linear modelling of pelagic fisheries of northern Chile was first performed using an univariate ANN model that considered only anchovy catches (Gutiérrez-Estrada *et al*., 2007). Studies by Gutiérrez-Estrada *et al*. (2009) and Yáñez *et al*. (2010) considered an ecosystem approach to the prediction of sardine and anchovy landings, respectively. A range of innovative tools for the EAA, such as dynamic models, is available to estimate the carrying capacity and to determine the temporal variability of environmental effects (*e.g.*, DEPOMOD (Particle Deposition Model): Cromey *et al*., 2002; MOM (Modelling Ongrowing fish farms Monitoring): Stigebrandt *et al*., 2004; FARM (Farm Aquaculture Resource Management Model): Ferreira *et al*., 2007).

This study aims to contribute to the EAF and the EAA and thereby improve the management of coastal systems, where fisheries and aquaculture occur or are being planned. The application of ecosystem indicators and models (GIS, carrying capacity, and ANN) will be exemplified using two case studies in Chile: predictions of anchovy (*Engraulis ringens*) abundance and spatio-temporal distribution of fishing grounds in the Chilean northern coastal region and predictions of the local-scale carrying capacity and the environmental effects of Pacific oyster (*Crassostrea gigas*) cultivation in the Valdivia Estuary (south-central Chile).

MATERIALS AND METHODS

The general approach used in this study was to apply and combine the EAF and EAA management assessment methods into a three-stage analysis, to evaluate the activities of an anchovy fishery and the aquaculture of the Pacific oyster in Chile (Fig. 1). Stage 1 considered spatio-temporal ecosystem indicators (fisheries, aquaculture, environmental, and regulatory), Stage 2 developed statistical relationships between the indicators, GIS, and other simulation models of the interaction between the environment and resources (*e.g.*, ANN and FARM), and Stage 3 analysed and validated the outputs of the model.

EAF case study: prediction of environmental variability effects on fisheries

The EAF case study focused on the prediction of the effects of environmental variability on a small pelagic anchovy fishery in the offshore and coastal area of northern Chile (Fig. 2a). This study area is influenced by the Humboldt Current System and is part of a highly productive marine ecosystem due to the transport of nutrients by large-scale horizontal advection and persistent coastal upwelling. In this area, the fishery is based successively on anchovy and sardine, and these noticeable changes in the type of fish caught are a result of changes in fishing effort and environmental fluctuations (Yáñez *et al*., 2001, 2008). Ocean climate changes have been related to alterations in the marine ecosystems on several spatial temporal scales (Chavez *et al*., 2003; Yáñez *et al*., 2003; Alheit & Ñiquen, 2004).

Data from anchovy fisheries, environmental (atmospheric and oceanographic) data, and regulatory data were used as ecosystem indicators in the EAF Stage 1 (Fig. 1, Table 1). Spatio-temporal data were obtained from satellite and fishing grids, and temporal data were obtained from monitoring stations and fishing ports. In Stage 2, environment-resource interactions were estimated using statistical relationships among ecosystem indicators. GIS modelling at local and daily scales were used to make predictions of PFG (Probable Fishing Grounds) for anchovy, using the methodology described in previous works (Silva *et al*., 2002, 2004; Yáñez *et al*., 2004). The PFG prediction model uses the relationships between environmental conditions and resource distributions to determine the optimal ranges of environmental conditions within fishing grounds. Additionally, ANN simulation models were used to predict the monthly anchovy abundance and to analyze relationships with environmental factors using the methodological approaches described in Gutiérrez-Estrada *et al*. (2007) and Yáñez *et al*. (2010). The ANNs models are mathematical structures capable of representing highly non-linear complex models that are not limited by assumptions on the functional relations among the involved variables (physical environment, biological, fisheries, others), when the data does not meet statistical assumptions, and having good ability to generalize when entering new data; in this sense, they present a great advantage over conventional models (Lek & Guégan, 1999; Özesmi *et al*., 2006). A multi-layer perceptron architecture model was used, calibrated with the Levenberg–Marquardt algorithm, to obtain prediction models for anchovy landings. Several accuracy measures were applied to assess ANN model performances. Predicted anchovy PFG and ANN abundances were validated in Stage 3. Data from 2000 were used for the validation of anchovy PFG, by comparing the predicted and observed fishing grounds and using the percentage of coincidences as an accuracy measurement. Data from 2005 were used for external validation, comparing the monthly observed and ANN estimated catches. To assess the performance of the ANN models, during the validation phases several measures of accuracy were applied: coefficient of determination (R^2), square root of the mean square error (RMSE), percent standard error of prediction (SEP), coefficient of efficiency (e), persistence index (PI), Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC).

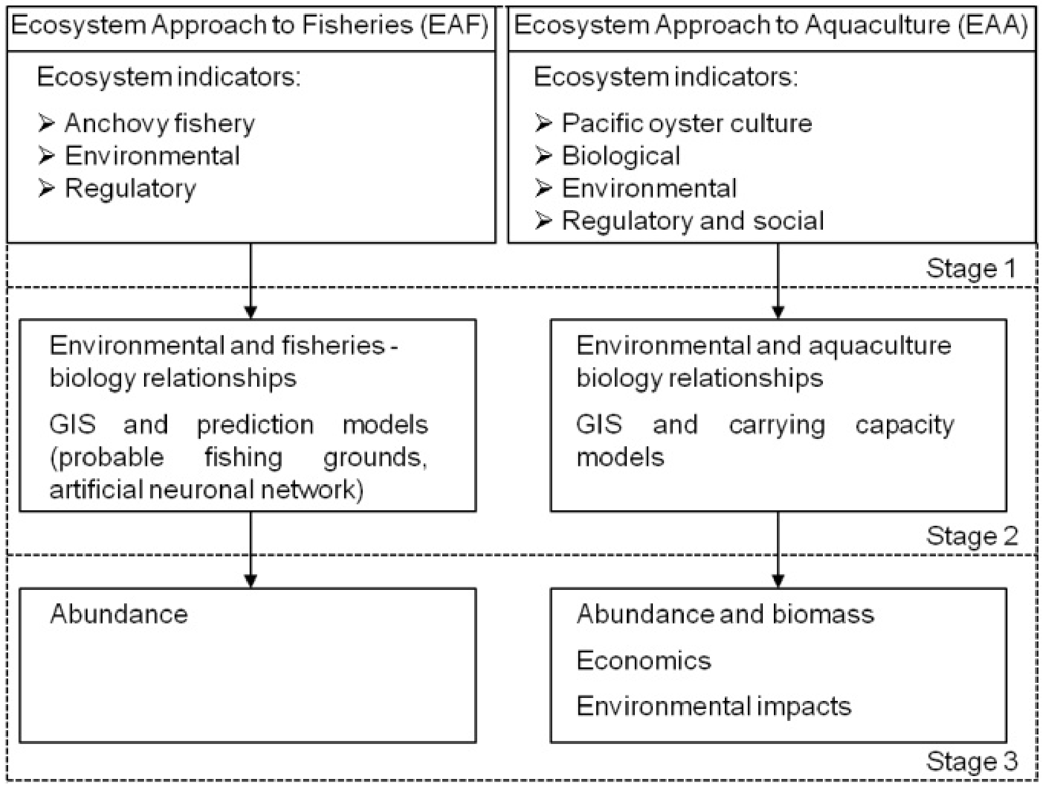

Figure 1. Methodological flow diagram of the EAF and EAA approaches.

Figura 1. Diagrama de flujo metodológico de los enfoques EAF y EAA.

EAA case study: prediction of suitable sites and carrying capacity of Pacific oyster aquaculture using FARM and GIS models

The EAA case study focused on the prediction of environmental and regulatory variability effects on the site suitability and carrying capacity of Pacific oyster aquaculture in the Valdivia Estuary (southern Chile) (Fig. 2b). The Valdivia Estuary is 40 km^2 in area and 170×10^6 m^3 in volume. It has a maximum depth of 18 m and receives a mean freshwater input of 15.7×10^9 m^3 yr^{-1}, primarily from the Valdivia River (Arcos *et al*., 2002). 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. Effluents from industry, agriculture, forestry, and urban sources from the city of Valdivia are discharged into the rivers and constitute the major cause of pollution and deterioration of water quality. The tidal regime at the mouth of the estuary (Bay of Corral) is semi-diurnal and has a tidal range between 0.5 and 1.5 m, with an average of 0.8 m (Pino *et al*., 1994). Tides are the main source of circulation energy for the estuarine system. Only a few studies and sampling campaigns have collected information on water quality, sediment characteristics, primary production, benthic fauna, and pollution in the estuary (Arcos *et al*., 2002; Ramírez, 2003; Palma-Fleming *et al*., 2004; Velázquez, 2005).

GIS and FARM models were used to test site selection in the Valdivia Estuary, to screen for potential oyster farming areas (Silva, 2009). The methodology used in this work is fully detailed in Silva *et al*. (2011). Stage 1 considers the collection of a range of ecosystem indicators, corresponding to the spatio-temporal data, from monitoring samples and other sources (Fig. 1, Table 1). Stage 2 uses a GIS multi-criteria evaluation (MCE) of sediment, water, and ecological quality data, to determine the suitability of aquaculture sites. Stage 2 also uses a detailed analysis with a farm-scale (FARM software, Ferreira *et al*., 2007) carrying capacity model, that simulates processes, by integrating a combination of physical and biogeochemical models, shellfish and finfish growth models, and screening models, to determine optimal shellfish aquaculture production, economic outputs (income and expenditure), and environmental effects (biodeposition, eutrophication

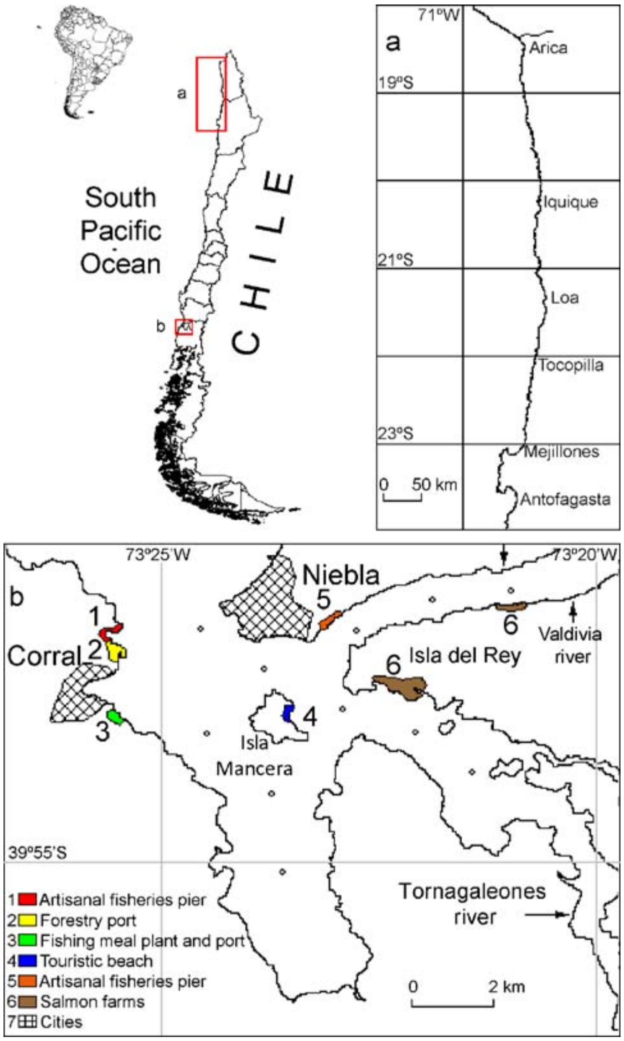

Figure 2. Study sites in the coastal area. a) Northern Chile, b) Valdivia Estuary.

Figura 2. Sitios de estudio. a) En el área costera Norte de Chile, b) estuario río Valdivia.

assessment, and nutrient emissions). The FARM model was selected for dynamic modelling because it provides all the necessary outputs, it is easy to use, and has been extensively tested (USA, Ferreira *et al*., 2008; European Union, Ferreira *et al*., 2009; China, Ferreira *et al.*, 2009; and Chile, Ferreira *et al*., 2010; Silva *et al.*, 2011) compared with other carrying capacity models available (*e.g.*, Chamberlain, 2002; DEPOMOD (Particle Deposition Model): Cromey *et al*., 2002; Bacher *et al*., 2003; MOM (Modelling-Ongrowing fish farms-Monitoring): Stigebrandt *et al*., 2004; Grant *et al*., 2007; Weise *et al*., 2009). The FARM model simulates the individual growth of the Pacific oyster in suitable sites of the Valdivia Estuary, taking into account the food supply and oceanographic conditions. It calculates the biomass distribution for the cultivated species, with emphasis on the harvestable weight class. The individual growth model used for the Pacific oyster is based on a net energy balance approach (Hoffmann *et al*., 1995; Kobayashi *et al*., 1997), and uses feeding, assimilation and metabolism functions that have been previously published by various authors (Kobayashi *et al*., 1997; Ren & Ross, 2001; Brigolin *et al*., 2009). The predicted individual growth of the Pacific oyster was validated using experimental growth curves previously determined by Möller *et al*. (2001), for the Valdivia Estuary.

RESULTS

Anchovy fishing grounds and abundance prediction models in northern Chile

A map of PFG estimated using GIS tools and satellite images of sea surface environmental conditions is shown in Figure 3. This figure is an example of how the prediction model of anchovy PFG can be applied at daily (temporal) and local (spatial) scales. The PFG model is supported by past evidence, showing the spatial and temporal distribution of anchovy, and by the optimal ranges of sea surface temperature (SST), thermal gradients (TGRs) and chlorophyll-*a* (Chl-*a*), that were recorded in the fishing zones. Anchovy were found in SSTs ranging from 16 to 23ºC, with an optimum range of 19 to 20ºC, and in TGRs from 0.3 to 3.5ºC/10 nm, with an optimum range of 0.8 and 2.1ºC/10 nm. For Chl-*a*, the range was between 0.2 and 6.0 mg m^{-3}, and the optimum range varied between 0.3 and 1.3 mg m^{-3}. In contrast, the coastal distribution of anchovy is related to areas with steep thermal gradients and high Chl-*a* levels, due to the permanent presence of coastal upwelling. The PFG image of the model output indicates areas of high catch probability according to the optimal environmental ranges. For example, the model output for the 1999-2000 La Niña event indicated that PFGs were distributed throughout the marine area of the study site, but were mainly present in the first 60 nm, and were primarily associated with thermal fronts and chlorophyll blooms that formed in specific coastal areas (Fig. 3). In 2000, the PFG model was successfully validated using data from the purse-seine fleet of northern Chile, which accounted for 74% of the coincidences among successful fishing grounds and the areas of high probability estimated by the model for a dataset of 120 observations.

For the anchovy ANN model, only the monthly STT of the Antofagasta station was considered as an environmental variable in the model, as the others factors were not significantly correlated to the

Table 1. Ecosystem indicators used in the EAF and EAA case studies.
Tabla 1. Indicadores ecosistémicos utilizados en los casos de estudio de EAF y EAA.

EAF indicators	EAA indicators
Anchovy fishery	Pacific oyster aquaculture
Landings, fishing effort, catch per unit effort	Farm dimensions, culture structures, culture period
Biological	Biological
	Natural mortality, seed weight, harvest weight
Environmental	Environmental
Atmosphere: Southern oscillation index	Water: current speeds, bathymetry, temperature,
Water: sea surface temperature, sea level, turbulence index, Ekman transport, thermal gradient, chlorophyll-*a*, bathymetry	salinity, total particulate matter, dissolved oxygen, chlorophyll-*a*, particulate organic matter, faecal coliform
	Sediment: grain size, metals (As, Cr, Cu, Fe, Mn, Pb), total organic matter, polycyclic aromatic hydrocarbons
	Ecological: Shannon biodiversity
Regulatory	Regulatory and social
Closed season	Unsuitable zones, salmon-farms, shipping, artisanal fisheries, management and exploitation areas of benthic resources

anchovy fisheries variables. The best errors estimated for the anchovy abundance prediction were associated with the 18:20:1 architecture. The ANN model explained 85% of the variance with an efficiency of 0.84. The persistence index was 0.83 with a brief lag between the observed and estimated anchovy abundance. The standard error of the prediction (34.15%), and the root mean square (RMS) values (19,022.07 tonnes), showed the scatter between the observed and estimated series of anchovy landings (Fig. 4). Landings integrate all environmental variability, which explains the great importance of landings in the sensitivity analysis of calibrated models.

Suitable sites and carrying capacity of the Pacific oyster in the Valdivia Estuary

The final spatial distributions of the multi-layer ecosystem indicators generated using GIS interpolation functions are shown in Fig. 5.

Figure 6 summarises the GIS MCE approach of the ecosystem indicators (constraints and factors), to generate a final map showing the site suitability. Results showed that suitable areas were spatially constrained by legally unsuitable zones, salmon farms, management and exploitation areas of benthic resources, shipping, salinity, total particulate matter, dissolved oxygen, chlorophyll-*a*, particulate organic matter, bathymetry, Mn, and total organic matter. Other factors were always within acceptable limits for the cultivation of the Pacific oyster. The FARM carrying capacity model was used for a detailed analysis of the oyster production, socio-economic outputs, and environmental effects (biodeposition, carbon removal, nutrient emissions, and eutrophication) of four sites from suitable areas (Niebla, Valdivia, Isla del Rey, and Tornagaleones) (Fig. 6).

In this work, the FARM model of the Pacific oyster was validated using experimental growth curves determined by Möller *et al*. (2001), for the Valdivia and Tornagaleones sites of the estuary. A significant relationship was found between the model outputs and the observed Pacific oyster growth ($P < 0.01$; Fig. 7).

Significant differences in the Pacific oyster aquaculture production and socio-economic results were obtained for the potential sites, at a standard seed density of 100 ind m^{-2}, with 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 rate of 0.35 yr^{-1} (Table 2). After the cultivation period, the Tornagaleones site showed the highest production and economic return of the cultivated population, with a total physical product (TPP) of 139.6 ton TFW, an average physical product (APP, output/input) of 11.64, and a harvest profit of 686 k€. The Niebla site showed the lowest production, with a TPP of 18.9 ton TFW,

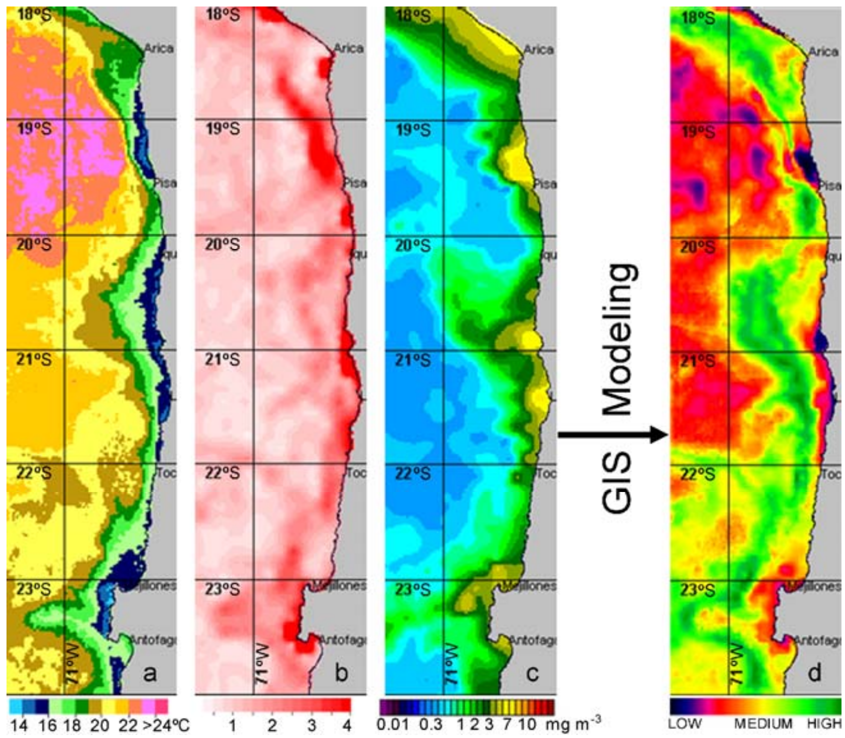

Figure 3. Example of daily satellite images of sea surface temperature (a), thermal gradient (b) and chlorophyll-*a* (c) as input ecosystem indicators and PFG map (d) as output of the GIS modelling. Example of the PFG modeling during La Niña 1999-2000.

Figura 3. Ejemplo de imágenes satelitales diarias de temperatura superficial del mar (a), gradiente térmico (b) y clorofila-*a* (c) como indicadores ecosistémicos de entrada y mapa de PFG (d) como resultado de la modelación con SIG. Ejemplo de modelación de PFG durante La Niña 1999-2000.

APP of 1.57, and a profit of 82.5 k€. These results suggested that the Tornagaleones site was the most promising site for the cultivation of Pacific oysters, due to rapid growth of the oysters and a good return on investments. Valdivia and Isla del Rey were satisfactory sites for Pacific oyster cultivation, and the Niebla area was less promising due to slow oyster growth and a marginal return on investments.

The FARM modelling results for the environmental impact of a standard seed density for Pacific oyster farms in the Valdivia Estuary are shown in Table 2. The negative environmental impact generated by Pacific oyster farms resulted from biodeposits; however, by definition, organically extractive cultures lower the concentration of the suspended organic particles in the water column, thus, leading to a net reduction of phytoplankton and detritus. The simulated results by the FARM model for the biodeposition of the potential Pacific oyster farms are shown in Table 2. The FARM model does not account for vertical turbulence, sediment erosion or diagenesis and thus only provided a precautionary estimate of biodeposition. For example, the natural sedimentation at the Tornagaleones site prior to shellfish stocking would lead to a gross deposition of approximately 7.43 kg m^{-2} yr^{-1} of particulate organic carbon (POC) and an equivalent sediment accretion rate of 7.52 mm yr^{-1}. At simulated stocking densities, the farm's carbon footprint corresponded to approximately 7.64 kg m^{-2} yr^{-1} POC, with a slightly higher accretion rate of 7.73 mm yr^{-1}. The effective rate of sediment organic enrichment due to cultivation was low (~0.1%) in the absence of mitigating factors. The excess biodeposition was thus partly due to the production of biodeposits by the oysters and partly due to the natural sedimentation of suspended particles, as they were advected across the farm area.

Positive environmental impacts are obtained from a carbon and nitrogen mass balance as a result of the depletion of these elements through the ingestion of phytoplankton and detrital organic material by oyster filtration and the return of these elements through excretion and elimination (Table 2). At a standard density, the Tornagaleones site showed the highest

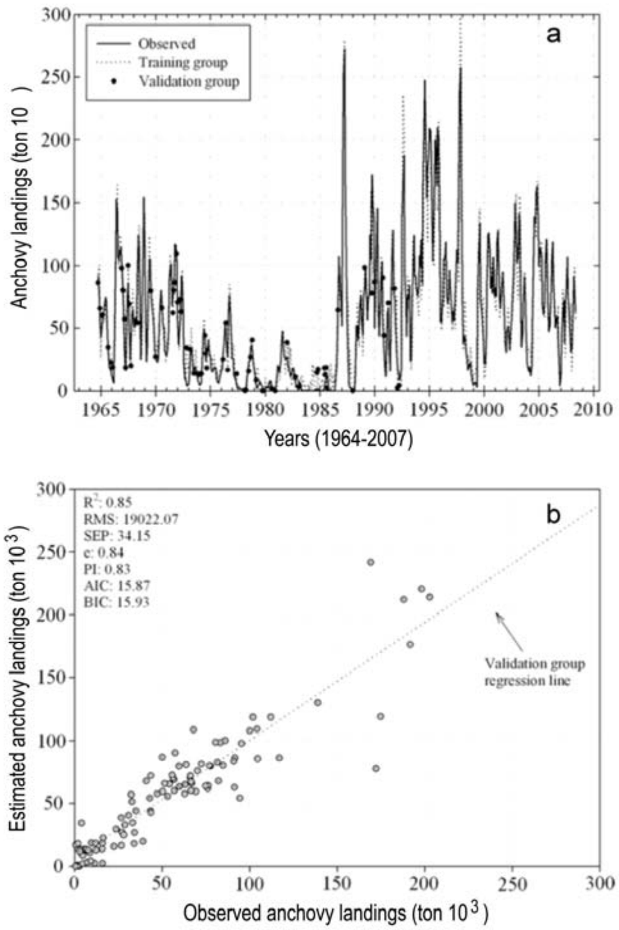

Figure 4. Prediction of the best anchovy artificial neural network model estimated. a) Monthly observed and predicted landings for calibration and validation sets, b) scatter plot between observed and predicted anchovy landings. Source*:* Yáñez *et al*. (2010).

Figura 4. Predicción del mejor modelo ANN estimado. a) Desembarques mensuales observados y previstos para los conjuntos de datos de calibración y validación b) dispersión entre los valores de desembarques de anchoveta observados y previstos. Fuente*:* Yáñez *et al*. (2010).

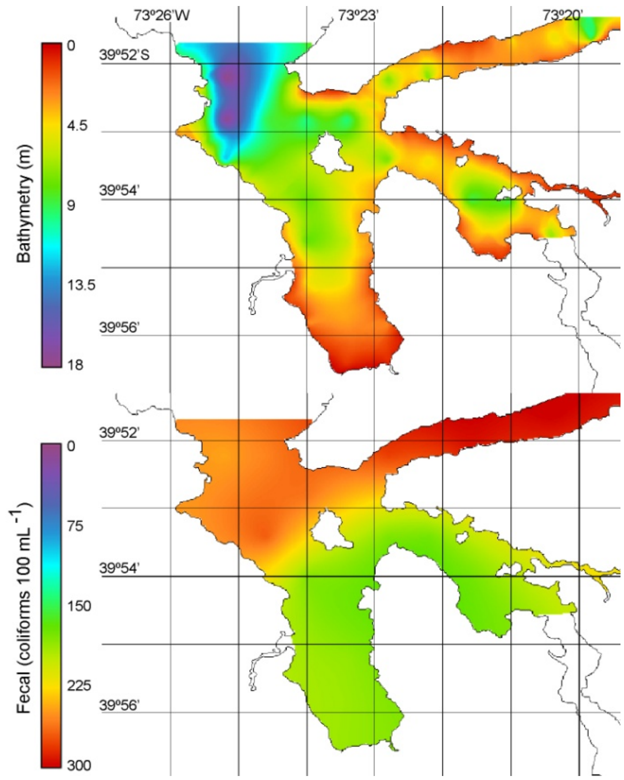

Figure 5. Example of image data of ecosystem indicators: bathymetry and concentration of faecal coliform in water.

Figura 5. Ejemplo de datos de imágenes de indicadores ecosistémicos: batimetría y concentración de coliformes fecales en el agua.

carbon (C) removal values, and the Niebla site showed the lowest C removal (phytoplankton + detritus) values in the standard scenario, with values of 69 ton C y^{-1} and 49 ton C yr^{-1} respectively. The Tornagaleones site had the highest net nitrogen (N) removal from the water due to the filtration of algae and detritus by oysters, with annualised net removals of 5.1 ton N yr^{-1}, which correspond to a nitrogen input of 1,549 population equivalents per year (PEQ yr^{-1}) in the standard scenario. The positive socio-economic impacts generated by the aggregate income of both shellfish sales and the substitution values of the reduction of land-based fertilizers or nutrient treatments are shown in Table 2. At standard densities, the Tornagaleones site showed the highest total income (691.7 k€) from shellfish sales (645.2 k€) and substitution costs of nutrient treatment (46.5 k€).

An indicator of eutrophication, at the local scale, was generated by the ASSETS (Assessment of Estuarine Trophic Status) model and implemented in the FARM model and was examined for the four potential oyster farms (Table 2). The eutrophication indicator score showed that the oyster farms had significant positive effects on the water quality in the Valdivia site, where the status improved from "Moderate" to "Good". Positive changes in the ASSETS score were observed for the Valdivia site because Chl-*a* concentrations were low due to high phytoplankton removal. The site was thus defined as a low eutrophication region (< 5 µg L^{-1}). The quality of the inflowing water at the Tornagaleones site was moderate; there was no effect of the oyster farms on outflowing water quality.

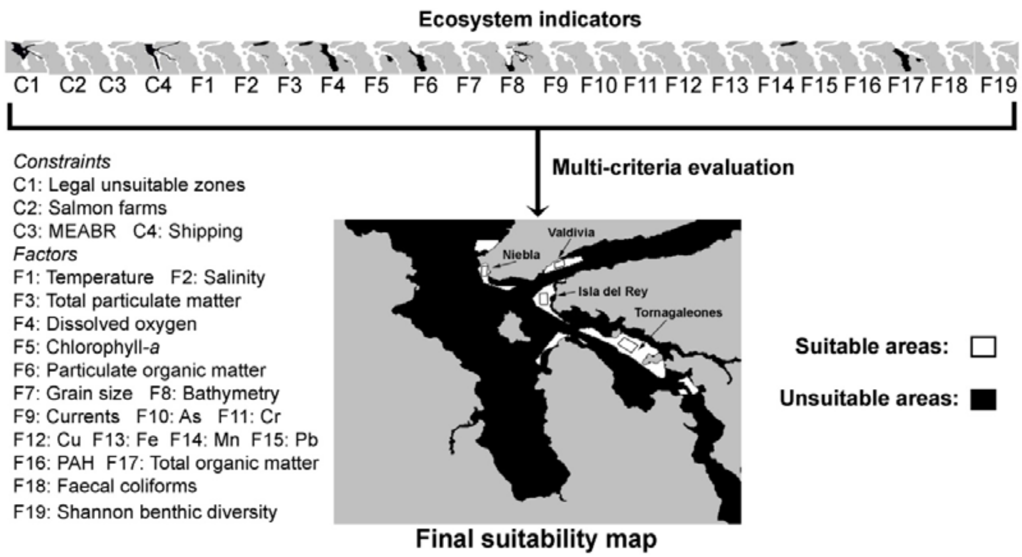

Figure 6. Example of GIS MCE and suitability map (Silva, 2009).

Figura 6. Ejemplo de evaluación multicriterio en SIG y mapa final de aptitud (Silva, 2009).

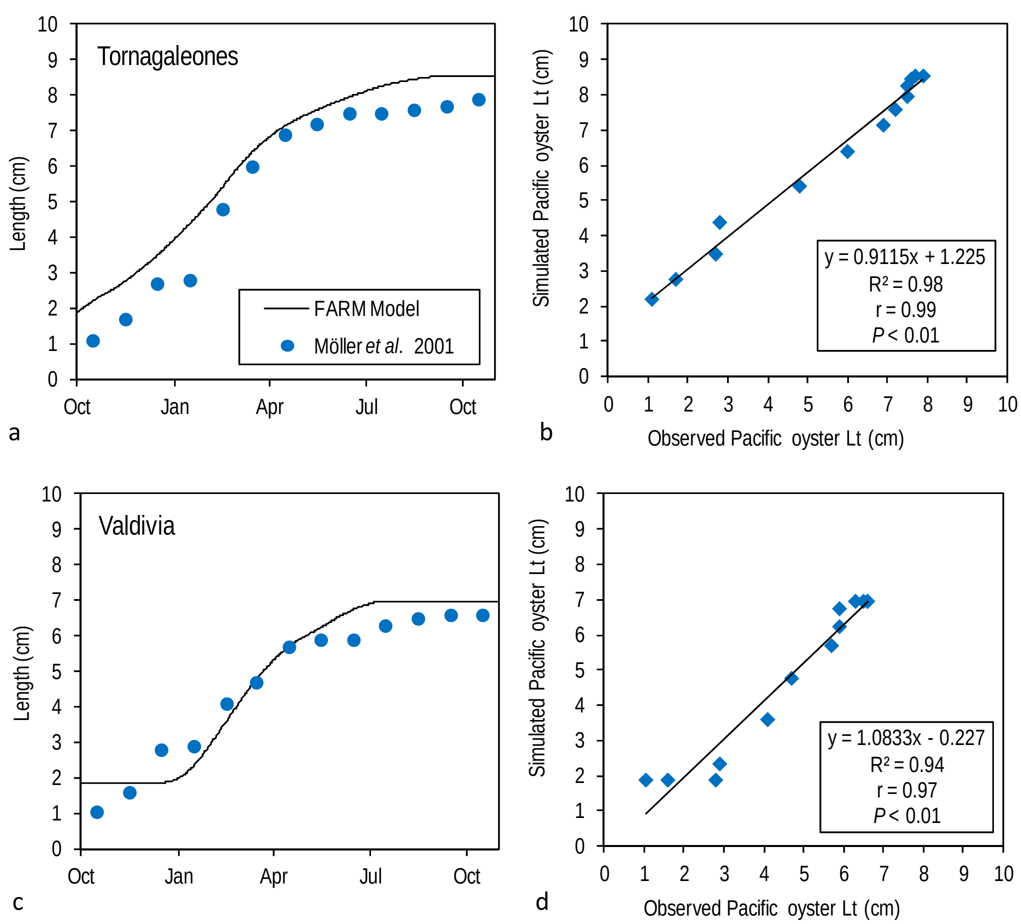

Figure 7. Validation of individual growth for the Pacific oyster in Valdivia Estuary, Chile. Lt: Length.

Figura 7. Validación del crecimiento individual de la ostra del Pacífico en el estuario del río Valdivia, Chile. Lt: longitud.

Table 2. Inputs and outputs of FARM model for standard seed density (100 ind m^{-2}) at four potential Pacific oyster farms in the Valdivia Estuary: Niebla (N), Valdivia (V), Isla del Rey (IR), and Tornagaleones (TG).

Tabla 2. Entradas y salidas del modelo FARM para una densidad de semillas estándar (100 ind m^{-2}) en cuatro potenciales granjas de cultivo de ostra del Pacífico en el estuario del río Valdivia: Niebla (N), Valdivia (V), Isla del Rey (IR) y Tornagaleones (TG).

Variable	N site	V site	IR site	TG site
Model inputs				
Farm area (m^2)	60,000	60,000	60,000	60,000
Seeding density (ton)	12	12	12	12
Culture period (days)	395	395	395	395
Seed weight (g TFW)	1.2	1.2	1.2	1.2
Harvest weight (g TFW)	90	90	90	90
Natural mortality (yr^{-1})	0.35	0.35	0.35	0.35
Model outputs				
Production				
Total Physical Product (ton TFW)	18.9	75.5	47.1	139.6
Average Physical Product [output/input]	1.57	6.3	3.93	11.6
Environmental impact				
Deposition of POC (kg m^{-2} yr^{-1})	4.41	7.58	9.45	7.64
Sediment organic enrichment (% POC yr^{-1})	4.34	6.83	8.27	6.88
Sediment accretion rate (mm yr^{-1})	4.46	7.67	9.56	7.73
Carbon removal (kg C yr^{-1})				
Phytoplankton removal	-7.681	-7.112	-4.046	-8.860
Detritus renoval	-41.069	-49.659	-47.930	-60.000
Nitrogen removal (kg N yr^{-1})				
Phytoplankton	-1.195	-1.106	-629	-1.378
Detritus	-6.389	-7.725	-7.456	-9.333
Excretion	471	466	347	576
Faeces	3.433	4.084	3.854	4.942
Mortality	70	62	41	81
Mass balance	-3.609	-4.220	-3.843	-5.111
Population equivalents (PEQ yr^{-1})	1.094	1.279	1.164	1.549
ASSETS score inflow	Good	Moderate	Good	Moderate
ASSETS score outflow	Good	Good	Good	Moderate
Income				
Harvest profit (k €)	82.5	365.7	223.6	686
Shellfish farming (k € yr^{-1})	87.3	349.0	217.7	645.2
Nitrogen removal (k € yr^{-1})	32.8	38.4	34.9	46.5
Total (k € yr^{-1})	120.1	387.4	252.7	691.7

Silva (2009)

DISCUSSION

The application of ecosystem indicators and models for the predictions of anchovy (*Engraulis ringens*) spatio-temporal distribution in the northern coastal region show the usefulness of GIS-based models for identifying suitable fishing grounds. The application of the PFG model demonstrates the utility of these tools for identifying suitable fishing grounds, under the exposed environmental conditions, specifically in critical climate episodes such as El Niño events. During La Niña events, an increase of medium and high catch probabilities was simulated due to the presence of cold and productive upwelled waters. This agrees with the findings observed by Blanco *et al.* (2002), suggesting that during La Niña events anchovy reappeared at their normal fishery locations and that their biomass was relatively high. In the context of integrated management, the PFG maps are considered to be critical for EAF and important from the perspective of the operators (Carocci *et al*., 2009).

Regarding the results of the application of ANN tools, the strong correlation between the estimated and observed time series of the anchovy abundance suggests that these models capture the trend of the historical data. Results from Gutiérrez-Estrada *et al*. (2007) showed that the anchovy landing series was autocorrelated, and anchovy catches with a lag of -1 was the most important variable. Moreover, anchovy landings are the longest analyzed fishing series, and an empirical orthogonal function analysis conducted between environmental fluctuations and landings found that the best simulation was obtained from the landing series (Yáñez *et al*., 2008). Furthermore, landings show clear interdecadal, interannual, and intraseasonal fluctuations, which may be directly related to the abundance of the resource. This is why landings are proposed as a proxy for the abundance of anchovy in northern Chile.

Results regarding the site selection for Pacific oyster 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. No significant impacts of shellfish farming on the benthos were 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 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 2). The net removal of carbon and nitrogen has direct relevance for integrated coastal zone management (Ferreira *et al*., 2007, 2009). Oyster culture can help to reduce symptoms of eutrophication by removing chlorophyll and thereby increasing water clarity, which promotes the growth of submerged aquatic vegetation and reduces the decomposition of organic material. This, in turn, reduces secondary eutrophication symptoms such as oxygen depletion (Bricker *et al*., 2003; Ferreira *et al*., 2007, 2009). The components of the eutrophication assessment, nutrient budget of shellfish farms (Brigolin *et al*., 2009; Ferreira *et al*., 2009), and the implementation of a nutrient credit trading in ICZM for aquaculture site selection are central to the FARM modelling approach.

Potential synergistic opportunities exist between the spatial components of the EAF and the EAA, in terms of sharing data (ecosystem indicators, *e.g.*, environmental, fisheries, aquaculture), and developing tools (*e.g.* remote sensing, sensors for environmental monitoring, GIS-based multi-criteria analysis and production models), methodologies and guidelines (Carocci *et al*., 2009; Aguilar-Manjarrez *et al*., 2010). An EAF review (Carocci *et al*., 2009) illustrated the use of GIS for several EAF-related projects and described a wealth of information, tools, models, and data that are relevant to the EAA (Aguilar-Manjarrez *et al*., 2010). Spatio-temporal analysis is essential, and the mapping and modelling of different scenarios are key contributions for implementation of the EAF and the EAA (Aguilar-Manjarrez *et al*., 2010). Several modelling approaches, relevant to the EAF, have been described by Plagányi (2007), and are a rich source of information from which the synergistic use of GIS between the EAF and the EAA can be identified. The main activities with spatial components common to the EAF and the EAA are minimising the impacts of fisheries and aquaculture on ecosystems (including social impacts), and anticipating environmental and anthropogenic impacts on aquaculture and fisheries.

There is a need to develop projects for the practical implementation of the EAF and the EAA. Finding sites for aquaculture has been and will continue to be a challenge; therefore, an application focused on the use of GIS and dynamic models for farm site selection in an EAA context (*e.g.*, Silva *et al*., 2011) would be useful. Particularly, this model could be applied and improved elsewhere, especially in data-poor environments.

Aquaculture and fisheries can be quite different, but they have many data needs in common (Aguilar-Manjarrez *et al*., 2010). Similarly, data and technical innovations applied for other purposes, such as coastal zone management and water resource assessments, can also be useful for aquaculture. For the sake of economy and to promote cooperation between aquaculture and fisheries, opportunities to recognise synergies should be pursued at all levels.

FAO workshops and publications on the EAF and EAA initiatives offer the opportunity to identify a number of mutually beneficial commonalities (*e.g.*, data and knowledge of species life history, ecology, capacity building, and modelling tools) as the bases for the development of synergies (Plagányi, 2007; Carocci *et al*., 2009; Aguilar-Manjarrez *et al*., 2010).

These synergies and commonalities can improve the management of fisheries and aquaculture by reducing the costs of data collection, data processing, spatial analysis, training and technical assistance, which represents a major task. Nevertheless, the implementation of the EAA is more complex than of the EAF for the following reasons (Soto *et al*., 2008): i) fisheries have extractive activities on ecosystems, while aquaculture represents a multifaceted industrial activity whose impact on the ecosystem is much more complex; ii) fishery activities have generated several international agreements, as the international community desires the fair distribution and conservation of common natural resources; iii) aquaculture is a productive industrial activity that primarily exists in natural public spaces (*i.e.*, marine and inland waters).

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REFERENCES

Aguilar-Manjarrez, J., J.M. Kapetsky & D. Soto. 2010. The potential of spatial planning tools to support the ecosystem approach to aquaculture. FAO, Rome. FAO, Fish. Aquacult. Proc., 17: 176 pp.

Alheit, J. & M. Ñiquen. 2004. Regime shift in the Humboldt Current ecosystem. Prog. Oceanogr., 60: 201-222.

Arcos, D., H. Peña, S. Núñez, J. Ortiz, L. Furet, S. Figueroa, A. Sepúlveda & H. González. 2002. Determinación de la capacidad de carga de las zonas estuarinas de los ríos Valdivia y Bueno, X Región. Informe Final proyecto FIP 2000-29: 622 pp.

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

Blanco, J.L., P. Barría, J. Castillo & L.P. Atkinson. 2002. Response of anchovy (*Engraulis ringens*) off northern Chile to the 1997-1998 El Niño-La Niña sequence. Invest. Mar., Valparaíso, 30(1): 107-108.

Bricker, S.B., J.G. Ferreira & T. Simas. 2003. An integrated methodology for assessment of estuarine trophic status. Ecol. Model., 169(1): 39-60.

Brigolin, D., G. Dal Maschio, F. Ramapazzo, M. Giani & R. Pastres. 2009. An individual based population dynamic model for estimating biomass yield and nutrient fluxes through an off-shore *Mytilus galloprovincialis* farm. Estuar. Coast. Shelf Sci., 82: 365-376.

Cabello, F.C. 2006. Heavy use of prophylactic antibiotics in aquaculture: a growing problem for human and animal health and for the environment. Environ. Microbiol., 8(7): 1137-1144.

Calvi, A.M., G. Allinson, P. Jones, S. Salzman, M. Nishikawa & N. Turoczy. 2006. Trace metal concentrations in wild and cultured Australian short-finned eel (*Anguilla australis* Richardson). Bull. Environ. Contam. Tox., 77(4): 590-596.

Carocci, F., G. Bianchi, P. Eastwood & G. Meaden. 2009. Geographic information systems to support the ecosystem approach to fisheries: status, opportunities and challenges. FAO Fish. Aquacult. Tech. Pap., 532: 101 pp.

Chamberlain, J. 2002. Modelling the environmental impacts of suspended mussel (*Mytilus edulis*) farming. Napier University, Edinburgh, 200 pp.

Chavez, F., J. Ryan, S. Lluch-Cota & M. Ñiquen. 2003. From anchovies to sardines and back: multidecadal change in the Pacific Ocean. Science, 299: 217-221.

Close, C.H. & G. Brent-Hall. 2006. A GIS-based protocol for the collection and use of local knowledge in fisheries management planning. J. Environ. Manage., 78: 341-352.

Cochrane, K.L., C.J. Augustyn, G. Bianchi, P. de Barros, T. Fairweather, J. Iitembu, D. Japp, A. Kanandjembo, K. Kilongo, N. Moroff, D. Nel, J.P. Roux, L.J. Shannon, B. van Zyl & F. Vaz Velho. 2007. Results and conclusions of the project "Ecosystem approaches for fisheries management in the Benguela Current Large Marine Ecosystem". FAO Fish. Circ., 1026: 167 pp.

Cromey, C.J., T.D. Nickell & K.D. Black. 2002. DEPOMOD modelling the deposition and biological effects of waste solids from marine cage farms. Aquaculture, 214(1-4): 211-239.

Delgado C.L., N. Wada, M.W. Rosegrant, S. Meijer & M. Ahmed. 2003. Fish to 2020: supply and demand in changing global markets. Penang (Malaysia): World Fish Center, 226 pp.

Diana, J.S. 2009. Aquaculture production and biodiversity conservation. BioScience, 59(1): 27-38.

Fabi, G., S. Manoukian & A. Spagnolo. 2009. Impact of an open-sea suspended mussel culture on macrobenthic community (Western Adriatic Sea). Aquaculture, 289: 54-63.

Food and Agriculture Organization (FAO). 2006. State of world aquaculture 2006. FAO Fish. Tech. Pap., 500: 145 pp.

Food and Agriculture Organization (FAO). 2008. Fisheries management. 2. The ecosystem approach to fisheries. 2.1 Best practices in ecosystem modeling for informing an ecosystem approach to fisheries. FAO Fish. Tech. Guidelines for Responsible Fisheries, No. 4, Suppl. 2, Add. 1: 78 pp.

Food and Agriculture Organization (FAO). 2009. State of World Aquaculture 2008. Fisheries and Aquaculture Department, Food and Agriculture Organization of the United Nations, Rome. [http://www.fao.org/docrep/011/i0250e/i0250e00.htm].

Ferreira, J.G., A.J.S. Hawkins & S.B. Bricker. 2007. Management of productivity, environmental effects and profitability of shellfish aquaculture – the Farm Aquaculture Resource Management (FARM) Model. Aquaculture, 264: 160-174.

Ferreira, J.G., H.C. Anderson, R.A. Corner, X. Desmit, Q. Fang, E.D. de Goede, S.B. Groom, H. Gu, B.G. Gustafsson, A.J.S. Hawkins, R. Hutson, H. Jiao, D. Lan, J. Lencart-Silva, R. Li, X. Liu, Q. Luo, J.K. Musango, A.M. Nobre, J.P. Nunes, P.L. Pascoe, J.G.C. Smits, A. Stigebrandt, T.C. Telfer, M.P. de Wit, X. Yan, X.L. Zhang, M.Y. Zhu, C.B. Zhu, S.B. Bricker, Y. Xiao, S. Xu, C.E. Nauen & M. Scalet. 2008. Sustainable options for people, catchment and aquatic resources. The SPEAR Project, an International Collaboration on Integrated Coastal Zone Management, Ed. IMAR - Institute of Marine Research/European Commission, Lisbon, 180 pp. Available at: http://www.biaoqiang.org/documents/SPEAR/book.pdf.

Ferreira, J.G., A. Sequeira, A.J.S. Hawkins, A. Newton, T. Nickell, R. Pastres, J. Forte, A. Bodoy & S.B. Bricker. 2009. Analysis of coastal and offshore aquaculture: application of the FARM model to multiple systems and shellfish species. Aquaculture, 289: 32-41.

Ferreira, J.G., J. Aguilar-Manjarrez, C. Bacher, K. Black, S.L. Dong, J. Grant, E. Hofmann, J.M. Kapetsky, P.S. Leung, R. Pastres, Ø. Strand & C.B. Zhu. 2010. Expert Panel Presentation V.3. Progressing aquaculture through virtual technology and decision-making tools for novel management. Book of Abstracts, Global Conference on Aquaculture September 2010. FAO/NACA/Thailand Department of Fisheries, Phuket, pp. 22-25.

García, S.M., A. Zerbi, C. Aliaume, T. Do Chi & G. Lasserre. 2003. The ecosystem approach to fisheries. Issues, Terminology, Principles, Institutional Foundations, Implementation and Outlook. FAO Fish. Tech. Pap., 443: 71 pp.

GESAMP (IMO/FAO/UNESCO/WMO/WHO/IAEA/UN/UNEP) Joint Group of Experts on the Scientific Aspects of Marine Pollution, 2001. Planning and management for sustainable coastal aquaculture development. GESAMP Report Studies, 68: 90 pp.

Grant, J., K.J. Curran, T.L. Guyondet, G. Tita, C. Bacher, V. Koutitonsky & M. Dowd. 2007. A box model of carrying capacity for suspended mussel aquaculture in Lagune de Grande-Entrée, Îles-de-la-Madeleine, Québec. Ecol. Model., 200: 193-206.

Gutiérrez-Estrada, J.C., C. Silva, E. Yáñez, N. Rodríguez & I. Pulido-Calvo. 2007. Monthly catch forecasting of anchovy *Engraulis ringens* in the north area of Chile. Non-linear univariate approach. Fish. Res., 86: 188-200.

Gutiérrez-Estrada, J.C., E. Yáñez, I. Pulido-Calvo, C. Silva, F. Plaza & C. Bórquez. 2009. Pacific sardine (*Sardinops sagax* Jenyns, 1842) landings prediction. A neural network ecosystemic approach. Fish. Res., 100(2): 116-125.

Hoffmann, E.E., E.N. Powell, J.M. Klinck & G. Saunders. 1995. Modelling diseased oyster populations I. Modelling *Perkinsus marinus* infections in oysters. J. Shellfish Res., 14(1): 121-151.

Holmer, M., D. Wildish & B.T. Hargrave. 2005. Organic enrichment from marine finfish aquaculture and effects on sediment biogeochemical processes. In: B.T. Hargrave (ed.). Environmental effects of marine finfish. Aquaculture. Springer, Berlin, pp. 181-206.

Jennings, S. 2005. Indicators to support an ecosystem approach to fisheries. Fish Fish., 6: 212–232.

Lek, S. & J.F. Guégan. 1999. Artificial neural networks as a tool in ecological modelling, an introduction. Ecol. Model., 120: 65-73.

Longdill, P.C., T.R. Healy & K.P. Black. 2008. An integrated GIS approach for sustainable aquaculture management area site selection. Ocean Coast. Manage., 51: 612-624.

Kalantzi, I. & I. Karakassis. 2006. Benthic impacts of fish farming: meta-analysis of community and geochemical data. Mar. Pollut. Bull., 52: 479-483.

Kapetsky, J.M. & J. Aguilar-Manjarrez. 2007. Geographic Information Systems, remote sensing and mapping for the development and management of marine aquaculture. FAO Fish. Aquacult. Tech. Pap., 458: 125 pp.

Kobayashi, M., E.E. Hoffmann, E.N. Powell & J.M. Klinck. 1997. A population dynamics model for the Japanese oyster, *Crassostrea gigas*. Aquaculture, 149: 285-321.

Meaden, G.J. 2009. Geographical Information Systems (GIS) in fisheries management and research. In: E. Moksness & B. Megrey (eds.). Computers in fisheries research, Springer, London, pp. 93-120.

Möller, P., P. Sánchez, A. Muñoz-Pedreros & J. Bariles. 2001. Cultivo de ostra japonesa (*Crassostrea gigas*) en un humedal estuarino del sur de Chile. Gestión Ambiental, 7: 65-78.

Özesmi, S., C. Tan & U. Özesmi. 2006. Methodological issues in building, training, and testing artificial neural networks in ecological applications. Ecol. Model., 195: 83-93.

Palma-Fleming, H., A.J. Asencio & E. Gutierrez. 2004. Polycyclic aromatic hydrocarbons in sediments and mussels of Corral Bay, South Central Chile. J. Environ. Monitor., 6: 229-233.

Pino, M., G. Perillo & P. Santamaría. 1994. Residual fluxes in a cross-section of the Valdivia river estuary. Estuar. Coast. Shelf Sci., 38: 491-505.

Plagányi, É.E. 2007. Models for an ecosystem approach to fisheries. FAO Fish.Tech. Pap., 477: 108 pp.

Radiarta, I.N., S. Saitoh & A. Miyazono. 2008. GIS-based multi-criteria evaluation models for identifying suitable sites for Japanese scallop (*Mizuhopecten yessoensis*) aquaculture in Funka Bay, southwestern Hokkaido, Japan. Aquaculture, 284: 127-135.

Rajitha, K., C.K. Mukherjee & R. Vinu-Chandran. 2007. Applications of remote sensing and GIS for sustainable management of shrimp culture in India. Aquacult. Eng., 36: 1-7.

Ramírez, P. 2003. Línea base en calidad de agua para la cuenca del Río Valdivia. Tesis de Ingeniería de Ejecución en Ambiente, Universidad de Santiago, Santiago, 135 pp.

Ren, J.S. & A.H. Ross. 2001. A dynamic energy budget model of the Pacific oyster *Crassostrea gigas*. Ecol. Model., 142: 105-120.

Sapkota, A., A.R. Sapkota, M. Kucharski, J. Burke, S. McKenzie, P. Walker & R. Lawrence. 2008. Aquaculture practices and potential human health risks: current knowledge and future priorities. Environ. Int., 34: 1215-1226.

Silva, C., 2009. Modelling of productivity, water quality effects and profit optimisation of Pacific oyster (*Crassostrea gigas*) farms: application of the FARM model and GIS in the Valdivia Estuary of Chile. Master Science Thesis, Erasmus Mundus European Joint Master in Water and Coastal Management, University of Algarve, Portugal, 62 pp.

Silva, C., R. Olivarí & G. Yany. 1999. Proposición metodológica para la determinación de distritos de aptitud acuícola mediante la aplicación de Sistemas de Información Geográfica (SIG). Invest. Mar., 27: 93-99.

Silva, C., K. Nieto, M.A. Barbieri & E. Yáñez. 2002. Expert systems for fishing ground prediction models: a management tool in the Humboldt ecosystem affected by ENSO. Invest. Mar., 30(1): 201-204.

Silva, C., K. Nieto, M.A. Barbieri, G. Martínez & E. Yáñez. 2004. EFISAT project: predictability of pelagic fishing ground off Chile using Remote Sensing and Geographical Information Systems. In: Nishida, P.J. Kailola & C.E. Hollingworth (eds.). International symposium on gis/spatial analyses in fishery and aquatic sciences proceedings T. Fishery GIS Research Group, Saitama, 2: 311-322.

Silva, C., J.G. Ferreira, S.B. Bricker, T.A. DelValls, L. Martín-Díaz & E. Yáñez. 2011. Site selection for shellfish aquaculture by means of GIS and farm-scale models, with an emphasis on data-poor environments. Aquaculture, 318: 444-457.

Soto, D., J. Aguilar-Manjarrez, C. Brugère, D. Angel, C. Bailey, K. Black, P. Edwards, B. Costa-Pierce, T. Chopin, S. Deudero, S. Freeman, J. Hambrey, N. Hishamunda, D. Knowler, W. Silvert, N. Marba, S. Mathe, R. Norambuena, F. Simard, P. Tett, M. Troell & A. Wainberg. 2008. Applying an ecosystem based approach to aquaculture: principles, scales and some management measures. In: D. Soto, J. Aguilar-Manjarrez & N. Hishamunda (eds.). Building an ecosystem approach to aquaculture. FAO Fisheries and Aquaculture Proceedings, 14: 15-35.

Stigebrandt, A., J. Aureb, A. Ervikb & P.K. Hansen. 2004. Regulating the local environmental impact of intensive marine fish farming III. A model for estimation of the holding capacity in the modelling-ongrowing fish farm-monitoring system. Aquaculture, 234: 239-261.

Tomassetti, P. & S. Porrello. 2005. Polychaetes as indicators of marine fish farm organic enrichment. Aquacult. Int., 13: 109-128.

Travers, M., Y.J. Shin, S. Jennings & P. Cury. 2007. Towards end-to-end models for investigating the effects of climate and fishing in marine ecosystems. Prog. Oceanogr., 75: 751-770.

Velázquez, D.M., 2005. Determinación de metales pesados en biota (*Mytilus chilensis*) y sedimentos de la bahía de Corral, provincia de Valdivia, X Región. Tesis de Químico Farmacéutico, Universidad Austral de Chile, 93 pp.

Vezzulli, L., M. Moreno, V. Marin, E. Pezzati, M. Bartoli & M. Fabiano. 2008. Organic waste impact of captured-based Atlantic bluefin tuna aquaculture at an exposed site in the Mediterranean Sea. Estuar. Coast. Shelf Sci., 78: 369-384.

Weise, A.M., C.J. Cromey, M.D. Callier, P. Archambault, J. Chamberlain & C.W. McKindsey. 2009. Shellfish-DEPOMOD: Modelling the biodeposition from suspended shellfish aquaculture and assessing benthic effects. Aquaculture, 288(3-4): 239-253.

Yáñez, E., M.A. Barbieri & C. Silva. 2003. Fluctuaciones ambientales de baja frecuencia y principales pesquerías pelágicas chilenas. In: E. Yáñez (ed.).

Actividad pesquera y de acuicultura en Chile. Pontificia Universidad Católica de Valparaíso, Valparaíso, pp. 109-121.

Yáñez, E., M.A. Barbieri, C. Silva, K. Nieto & F. Espíndola. 2001. Climate variability and pelagic fisheries in northern Chile. Prog. Oceanogr., 49: 581-596.

Yáñez E., C. Silva, K. Nieto, M.A. Barbieri & G. Martínez. 2004. Using satellite technology to improve the Chilean purseine fishing fleet. Gayana, 68(2): 578-585.

Yáñez, E., F. Plaza, J.C. Gutiérrez-Estrada, N. Rodríguez, M.A. Barbieri, I. Pulido-Calvo & C. Bórquez. 2010. Anchovy (*Engraulis ringens*) and sardine (*Sardinops sagax*) abundance forecast off northern Chile: a multivariate ecosystemic neural network approach. Prog. Oceanogr., 87(1-4): 242-250.

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Yáñez E., S. Hormazabal, C. Silva, A. Montecinos, M.A. Barbieri, A. Valdenegro, A. Ordenes & F. Gómez. 2008. Coupling between the environment and the pelagic resources exploited off North Chile: ecosystem indicators and a conceptual model. Lat. Am. J. Aquat. Res., 36(2): 159-181.

Zhang, J., P.K. Hansen, J. Fang, W. Wang & Z. Jiang. 2009. Assessment of the local environmental impact of intensive marine shellfish and seaweed farming-Application of the MOM system in the Sungo Bay, China. Aquaculture, 287: 304-310.