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Modelling of interactions between inshore and offshore aquaculture

J.G. Ferreira [a,*], C. Saurel [a], J.D. Lencart e Silva [b], J.P. Nunes [b], F. Vazquez [a]

[a] New University of Lisbon, Faculty of Sciences and Technology, Centre for Ocean and Environment (IMAR), DCEA, FCT, Qta Torre, 2829-516 Monte de Caparica, Portugal
[b] University of Aveiro, CESAM & Dept. Environment and Planning, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal

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ABSTRACT

Offshore aquaculture is the subject of intense debate, focusing on feasibility, sustainability, and the potential for effective expansion in the context of competing uses of the coastal zone, and a world requirement for an additional thirty million tonnes of aquatic products by 2050.
A modelling framework that integrates the SWAT model for the watershed, Delft3D for ocean circulation, and the EcoWin model for long-term (10 year) ecological simulations, was developed for integrated analysis of catchment, inshore waters, and offshore aquaculture, providing an approach that addresses production, environmental effects, and disease interactions. This framework was tested using a case study in SE Portugal, for a system-scale modelling domain with an ocean area of 470 km^2 and a coastal watershed area of 627 km^2. This domain contains an inshore area of 184 km^2 (Ria Formosa) subject to multiple (often conflicting) uses, including aquaculture of the high value (farmgate price > 10 € kg^{-1}) clam *Tapes decussatus*, and one of the first offshore aquaculture parks in the world, located at distance of 3.6 nm from the coast, at a water depth of 30–60 m, with an area of 15 km^2. The park contains 60 leases, of which at most 70% are for finfish cage culture, and at least 30% for bivalve longline culture.
A substantial part of the dissolved nutrients required to drive primary production that constitutes the food source for clams originates from the coastal catchment. Although stakeholder perception is that nutrients are mainly linked to point-source discharges from wastewater treatment plants, watershed modelling indicates that 55% of the nitrogen and 70% of the phosphorus loads are from diffuse sources.
The residence time of waters in the inshore area is low (1–2 days), and consequently pelagic primary production takes place offshore, and drives inshore clam production. The longline culture of Mediterranean mussels (*Mytilus galloprovincialis*) in the offshore park reduces inshore food availability for clams: simulations suggest that a 3% decrease in clam yields will occur due to offshore mussel cultivation, at a cost of 1.2 million €. This is offset by revenue from offshore culture, but is a source of stakeholder conflict.
Potential disease spread between the offshore and inshore systems was analysed using a particle tracking model, and allowed the development of a risk exposure map. This illustrates the challenges posed by hydrodynamic connectivity with respect to biosecurity of aquaculture and fisheries, both inshore and offshore.
The model framework was also used for optimisation of stocking density, and analysis of combined culture of finfish and shellfish, both in terms of production and environmental effects. In the offshore aquaculture park, the models suggest that integrated multi-trophic aquaculture (IMTA) of gilthead bream (*Sparus aurata*) and Mediterranean mussels allows for an increased harvestable biomass of mussels, particularly at higher stocking densities, and offsets some of the negative externalities of finfish culture.
By quantifying issues such as reduced yields for inshore stakeholders due to offshore activity, and illustrating the need for strong governance to offset disease risks, dynamic models make a valuable contribution in assessing the feasibility of offshore aquaculture, and the general principles that should underpin licensing and regulation of this sector.
We stress the need to go beyond the conventional spatial planning toolset in order to ensure an ecosystem approach to aquaculture, and the opportunities that exist for applying a systems framework in an information economy, where the capital costs of software and data have been sharply reduced.

1. Introduction

Offshore aquaculture has been the subject of considerable discussion in recent years (Buck and Krause, 2012; Buck et al., 2004; Kapetsky et al., 2013; Pérez et al., 2003a; The Interagency Ocean Policy Task Force, 2010; Troell et al., 2009), leading to initiatives such as the Bremerhaven

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

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Declaration (Rosenthal et al., 2012a, 2012b), which establishes a roadmap for its development.

The term 'Offshore' does not have a legal definition comparable to the UN Convention of the Law of the Sea (UNCLOS) terms 'Territorial waters' and 'Exclusive Economic Zone' (Rosenthal et al., 2012a). For the purpose of this work, we have adopted the definition proposed by Drumm (2010), and adopted by FAO (Kapetsky et al., 2013): "In general Offshore Aquaculture may be defined as taking place in the open sea with significant exposure to wind and wave action, and where there is a requirement for equipment and servicing vessels to survive and operate in severe sea conditions from time to time. The issue of distance from the coast or from a safe harbour or shore base is often but not always a factor."

'Significant' is qualified in Ryan (2004) using a classification system based on the significant wave height H_s, where classes 3–5 correspond to medium ($H_s = 1.0–2.0$), high ($H_s = 2.0–3.0$) and extreme ($H_s > 3.0$).

Mooring systems (Jensen et al., 2007; Shainee et al., 2013), cultivation structures (Huang et al., 2006; Suhey et al., 2005), and automated feed delivery (Fullerton et al., 2004) are presently much better adapted to the challenges of the offshore environment, allowing aquaculture to take place further offshore, and well below the sea surface, thus avoiding the effects of wind, surface waves, and storm events.

In inshore waters, a typical state of the art salmon (*Salmo salar*) or rainbow trout (*Oncorhynchus mykiss*) farm uses polar cages with a volume in excess of 88,000 m^3, a cage depth of 45 m, and a stock of 200,000 fish; moreover, these numbers will tend to increase in the future due to economies of scale. Although fjordic systems in Norway and elsewhere may be deep enough to accommodate such structures while still maintaining a buffer depth below the cage to minimise organic enrichment of bottom sediments, in many inshore areas the water column will not extend to depths of 50 m or more to permit finfish culture on that scale (e.g. Kapetsky et al., 2013).

In addition, there are major obstacles to licensing of inshore culture in Europe and North America. These include:

1. Competitive use of the shoreline for recreation, shipping lanes, and marine protected areas (Tiller et al., 2012);
2. Environmental effects of aquaculture on the coastal environment (Grigorakis and Rigos, 2011; Holmer, 2010);
3. Environmental effects of the coastal environment on aquaculture, e.g. due to eutrophication or xenobiotics (Silva et al., 2011);
4. Social objections to siting, including concerns such as the viewshed of aquaculture structures (Hunter, 2009; Pérez et al., 2003b).

North America presently imports 86% of its aquatic products, leading to a seafood trade deficit in excess of \$9 billion (Tiller et al., 2013). Europe has a similar imbalance, and runs a seafood trade deficit of over \$10 billion (adapted from Food and Agriculture Organization of the United Nations, 2012). If there is some reduction of this deficit, substantial employment opportunities may potentially be created in both continents. Over the coming years, demand for aquatic products in developed countries is projected to increase (Food and Agriculture Organization of the United Nations, 2012), as consumers are encouraged to adopt a healthier diet – this increase cannot come from wild fisheries since capture rates are flatlining and will continue to do so in the foreseeable future. Moreover, aquaculture imports from Asia, responsible for about 90% of global production, will become more costly, and potentially more scarce, as the purchasing power of domestic consumers in China and SE Asia increases. As a consequence, given the constraints to inshore aquaculture, the offshore alternative appears to be one of the potential sustainable options for the developed world to reduce its dependency on imported marine seafood over the coming decades.

However, offshore aquaculture presents a number of significant challenges:

1. Optimal siting is a trade-off among factors such as depth and distance to port (Kapetsky et al., 2013);
2. Despite advances in feed automation (Fullerton et al., 2004; Menicou and Vassiliou, 2010), finfish culture requires that feed barges be regularly replenished, and locations that are continuously inaccessible over several days pose a huge risk to stock, and may well be uninsurable;
3. For shellfish culture, or finfish and shellfish in Integrated Multi-Trophic Aquaculture (IMTA), the availability of natural feed is critical (Pogoda et al., 2011);
4. The interactions between offshore culture and uses of inshore waters, which may also include aquaculture, must be carefully analysed, since potential multilateral effects may threaten the livelihood of existing stakeholders (Diana et al., 2013).

In order to understand these challenges, with particular reference to system-scale interactions, an integrated modelling approach seems to be a promising tool. Integrated models that provide an overall picture of production and environmental effects of aquaculture in coastal estuaries and bays have been extensively tested (Ferreira et al., 2008; Filgueira and Grant, 2009; Filgueira et al., 2010; Gangnery et al., 2004; Nobre et al., 2005, 2010; Nunes et al., 2011; Zhang et al., 2009); recently, farm-scale modelling was applied to analyse the performance of offshore aquaculture, both in monoculture and IMTA (Ferreira et al., 2012a). Kapetsky et al. (2013) provide a comprehensive study of the conditions necessary for successful aquaculture in offshore environments, and its potential on a global scale. However, to the best of our knowledge, an analysis combining the inshore and offshore components is currently lacking.

This work presents a state-of-the-art modelling framework, at a scale appropriate to deal with a coupled inshore–offshore system, in order to assess the sustainability and challenges to coastal management of offshore aquaculture operations. It additionally recognizes that there are significant issues that are not amenable to mathematical simulation, and analyses various aspects of governance that form an integral part of management for sustainability. In so doing, we draw upon an extended body of work on this subject, with particular reference to Olsen et al. (1998), and Olsen (2003).

Our main objectives are:

1. To examine the production, environmental effects, and economic performance of offshore aquaculture, using an existing aquaculture park as a case study;
2. To analyse the potential effects of offshore shellfish culture on existing uses of inshore waters, in critical areas such as production and disease;
3. To use the outcomes of this combined approach to propose guidelines for harmonious development of inshore and offshore aquaculture, together with other coastal uses, following the Ecosystem Approach to Aquaculture (EAA, Aguilar-Manjarrez et al., 2010; Soto et al., 2008).

2. Methodology

2.1. Overview

A general modelling framework to analyse an inshore–offshore system such as the one described below must resolve the essential components of both elements. For the inshore coastal zone, this includes the fluxes of materials across the land–ocean interface, and the circulation of water and distribution of water properties over a relatively broad coastal domain, extending beyond the relevant offshore areas. In addition, the relevant ecosystem compartments must be part of such a framework. Furthermore, because the constituent models vary in

Table 1
FORWARD–COEXIST Inshore and offshore modelling framework: models, objectives, scope and scale.

Model	Objective	Scope	Scale (space, time)
SWAT (Soil and Water Assessment Tool)	Discharge of water, nutrients, and sediment from the catchment, based on hydrological response units	Loading to coastal water, land-use scenarios to force primary production and other processes at the system scale	Entire catchment divided into sub-basins to match ecological model boxes, annual cycle providing daily load data
Delft3D-FLOW three-dimensional hydrodynamic model	Circulation in inshore and offshore waters	Support for definition of ecological model boxes, water flows across these boxes, risk analysis for disease based on hydrodynamic connectivity, local effects of WWTPs	Full system domain (Fig. 2), detailed circulation. 33,000 grid cells (up to 30 m resolution in the narrows), 7 vertical layers. One year, 30 minute flow data
AquaShell individual shellfish model	Individual growth of clams, oysters (inshore bottom culture) and mussels (offshore rope culture)	Growth and environmental effects based on physiology, input to population models, used in both system-scale and local-scale models	No spatial dimension, runs over a typical culture cycle for validation of growth curves and endpoints
AquaFish individual finfish model	Individual growth of gilthead bream, including determination of FCR	Growth and environmental effects based on physiology, input to population models, used in both system-scale and local-scale models	No spatial dimension, runs over a typical culture cycle for validation of growth curves and endpoints
EcoWin ecological model	System-scale simulations of inshore and offshore components of the ecosystem	Key biogeochemical cycles, finfish and shellfish growth and population dynamics, production of marketable cohort, environmental effects	Full system domain (Fig. 2), 35 boxes, 2 vertical layers, decadal period, 30 m timestep
FARM (Farm Aquaculture Resource Management) model	Farm-scale simulations of onshore and inshore aquaculture for shellfish, finfish, and IMTA	Finfish and shellfish growth and population dynamics, production, environmental effects, and economics	Local domain, using both measured environmental drivers and modelled output from EcoWin. One culture cycle
Geographic Information Systems (GIS)	Interfacing among SWAT, Delft3D-FLOW, and EcoWin, treatment and presentation of results	Use of multiple layers and classification algorithms to process and present data from dynamic models	Integrated time-series analysis, system-wide spatial scale

time scale from days to decades, the utility of the framework depends on the flexibility of the underlying components to deal with this variability.

The overall framework is illustrated in Table 1 and Fig. 1, and details of the various models are given in Ferreira et al. (2008, 2012a), Lencart e Silva et al. (2010), Nobre et al. (2010), and Nunes et al. (2013). In addition to the models, measured data were used to estimate nutrient inflows from waste water treatment plants (WWTP) and from bottom sediments (Falcão and Vale, 1998), with the latter assumed to come in a large part from contaminated coastal aquifers (see Stigter et al., 2007).

2.2. Study area

The case study area (Fig. 2) used for application of this framework combined work from the FORWARD (http://goodclam.org) and COEXIST (http://coexistproject.eu) research projects. The former analysed the sustainable management of inshore coastal resources, with a focus on aquaculture of the good clam, *Ruditapes decussatus*, and the latter studied a designated aquaculture park in the adjacent offshore area. The concurrent execution of both projects provided the leverage to analyse the interactions of existing and planned developments, both inshore and offshore.

The Ria Formosa (36° 95′ 87″ to 37° 17′ 53″N and 8° 04′ 97″ to 7° 51′ 69″ W) is a complex inshore coastal system, located in the Algarve province of southern Portugal (Fig. 2). The Ria is located on the leeward coast of the Algarve, has a length of 55 km, and an area of 184 km^2. Two peninsulas (Cacela and Ancão) and five barrier islands (Culatra, Barreta, Armona, Tavira and Cabanas) form the land boundaries, which enclose a shallow lagoon. These islands are separated by tidal inlets which lead into a dendritic channel system. The volume of the Ria varies between 45 and 210×10^6 m^3, for a tidal range between 0.9 and 3.0 m. Water temperature oscillates between 16 and 29 °C and salinity is about 36 psu.

The Ria Formosa is simultaneously a marine protected area, Portugal's most productive aquaculture zone, and the focus of other economic activities, including fishing, salt extraction, and tourism – all these must be reconciled in order to coexist harmoniously. The watershed draining to the Ria Formosa has an area of about 745 km^2 and high spatial complexity; it is divided into two main regions, mountains and loamy plains ('barrocal'). The mountain region has a more humid climate, poor soils, and relatively impermeable bedrock; it is covered by Mediterranean shrubland and less intensive agriculture, and is drained by the two main rivers: Rio Gilão and Ribeira de Almargem. The 'barrocal' has a drier climate, with more fertile soils and highly permeable bedrock with several aquifers; this allows the co-existence of rainfed orchards with groundwater-irrigated intensive orchards and horticulture. The catchment is drained by small streams with a torrential regime. The cities of Faro, Olhão, and Tavira are the main economic and tourist centres, and input nutrients to the Ria through discharges from WWTP.

Aquaculture of good clam is estimated to yield about 5000 tonnes live weight per year, corresponding to an annual income of about 50 million €, based on a farmgate price of 10 € kg^{-1}, and providing direct employment for 4000–6000 people. Challenges to the industry include falling harvests in recent years, elevated summer mortalities, and endemic infection with the protozoan parasite *Perkinsus marinus* (Dermo). In addition, some parts of the Ria Formosa occasionally exhibit concentrations of enteric bacteria that exceed the limits of the EU Shellfish Waters Directive (2006/113/EEC) for Class A status, making shellfish depuration mandatory.

In 2008, the Portuguese government designated a 15 km^2 offshore area located at a distance of 3.6 nm from the coast, at a water depth of 30–60 m (Fig. 2), south of the Ria Formosa barrier island system, for IMTA. Significant wave heights $H_s = 4.2–6.5$ m were recorded for a number of extreme events, including six storms in 2009 (Almeida et al., 2012), the usual H_s range being in the medium class (Ryan, 2004). The aquaculture park contains 60 leases, each with a cultivation area of 80,000 m^2, i.e. about 30% of the overall area is effectively farmed, the remainder being navigation channels and buffer zones. A maximum of 70% of the leases are for finfish culture, and a minimum of 30% for bivalve shellfish. The potential interactions between this new area, probably the first commercial IMTA aquaculture park in Europe, and the adjacent inshore waters are substantial.

2.3. Model development and implementation

The general framework shown in Fig. 1 was used to analyse both the inshore and offshore components of the system. The objective, scope, and scale of the different models are briefly reviewed in Table 1. All models were applied to reproduce the year between October 2007 and September 2008 (comprising a full hydrological year, i.e. a rainy and a dry season), during which the climate was representative of a typical year in this region.

A detailed description of the application of these models to the inshore part of the system, validation of outputs, and key results, has been published elsewhere (e.g. Ferreira et al., 2012a, 2012b, 2013) and will not be addressed here, except where pertinent to the analysis of inshore–offshore interactions. The system-scale model was validated against measured concentrations of nutrients and phytoplankton, individual clam growth curves, and reported landings.

Aquaculture in the offshore park was simulated using two different approaches:

1. The performance of the park was analysed through an application of the Delft3D-FLOW and EcoWin models (Fig. 3). The FARM model was not considered appropriate for local-scale simulation given (i) the size of the designated area; and (ii) the complexity of water circulation in the park. Since the resolution of Delft3D-FLOW is of the order of the size of individual leases, the circulation patterns were simulated in detail, and the results were used to drive the ecological model for a cultivation cycle (Fig. 3).

An analysis of marginal production, and performance using different options of monoculture and IMTA, was performed by running EcoWin with different stocking densities and spatial distribution of Mediterranean mussel, *M. galloprovincialis*, and gilthead bream, *S. aurata*;

2. The interaction of the offshore park with the inshore component of the system was examined through an application of the two models above. The focus areas were (i) shellfish yields and (ii) disease. For shellfish yield analysis, a comparative study was executed using EcoWin to 'switch on' the offshore park (Fig. 3), considering it to be fully stocked with mussels, and examining the effects on inshore clam harvest. For the disease component, Delft3D-FLOW was used to analyse the hydrodynamic connectivity between the offshore area and the leases inside the Ria Formosa that are used for clam culture, and to generate risk maps. This was done by simulating an emission of virus particles from the park, and mapping their distribution over a spring–neap cycle. The simulation considered a virus concentration of up to 2×10^6 ml^{-1}, with background release during the first 2 days, high release on days 3, 4, and 5, followed by a reduction by two orders of magnitude on the last day.

A complementary study of governance issues was supported partly by the outcomes of these models, and partly through stakeholder consultation and a review of best practice in other parts of the world.

3. Results and discussion

Results are shown for nutrient loading, primary production, and inshore clam culture using the modelling framework. The offshore aquaculture sub-model is then used to examine the effects of different culture combinations on yield and environment. Finally, the two models are combined to analyse interactions between offshore aquaculture and inshore activities.

3.1. Standard model

A synthesis of watershed loading results from SWAT, together with WWTP data, is shown in Figs. 4 and 5. The results illustrate that, contrary to the perception of clam culture stakeholders, about 55% of the nitrogen and almost 70% of the phosphorus input from land is due to diffuse sources, mostly via sediments.

Additionally, because precipitation is torrential (Fig. 5), much of the stream network nutrient loading is confined to a few days of heavy rainfall. This contribution occurs as a series of spikes associated with peak river discharges. While daily WWTP and sediment loads are relatively constant (0.7 to 1.8 tons of nitrogen, and 0.1 to 0.6 tons of phosphorus), stream network loads are concentrated in periods with high rainfall and streamflow; stream loads are usually negligible, but daily loads of 27 tons of nitrogen and 15 tons of phosphorus are attained during the maximum flow period.

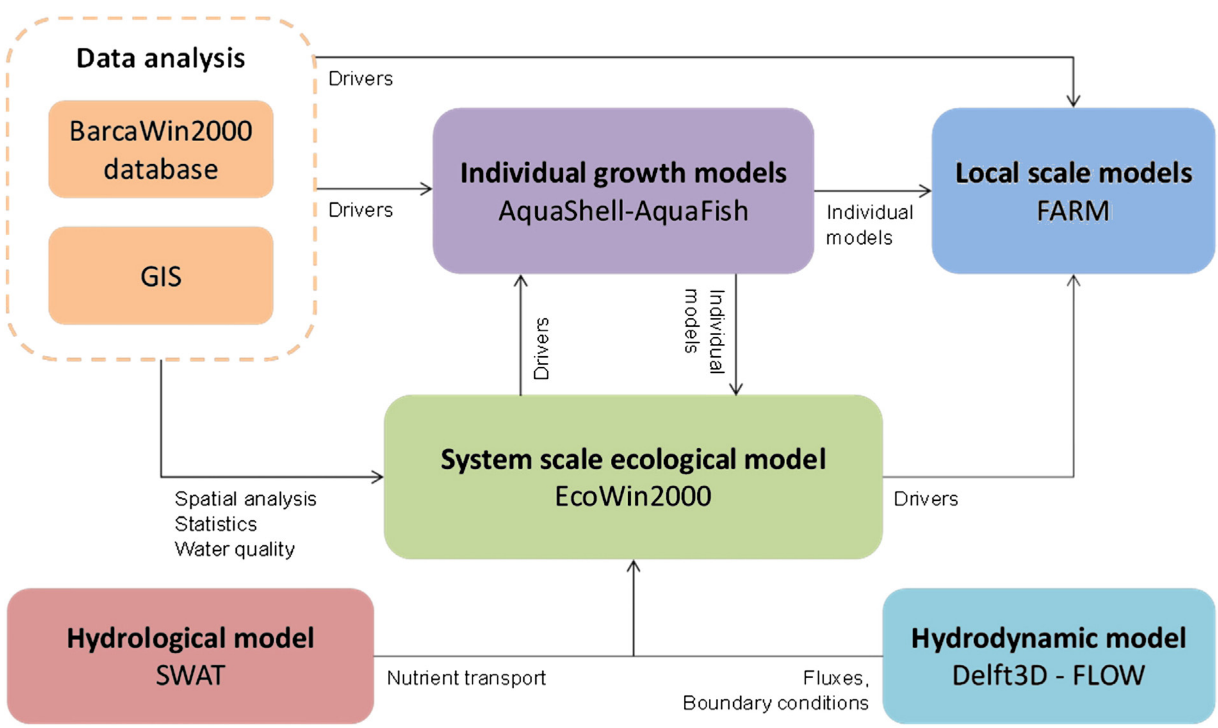

Fig. 1. Modelling framework for analysing interactions between the inshore coastal zone and offshore aquaculture.

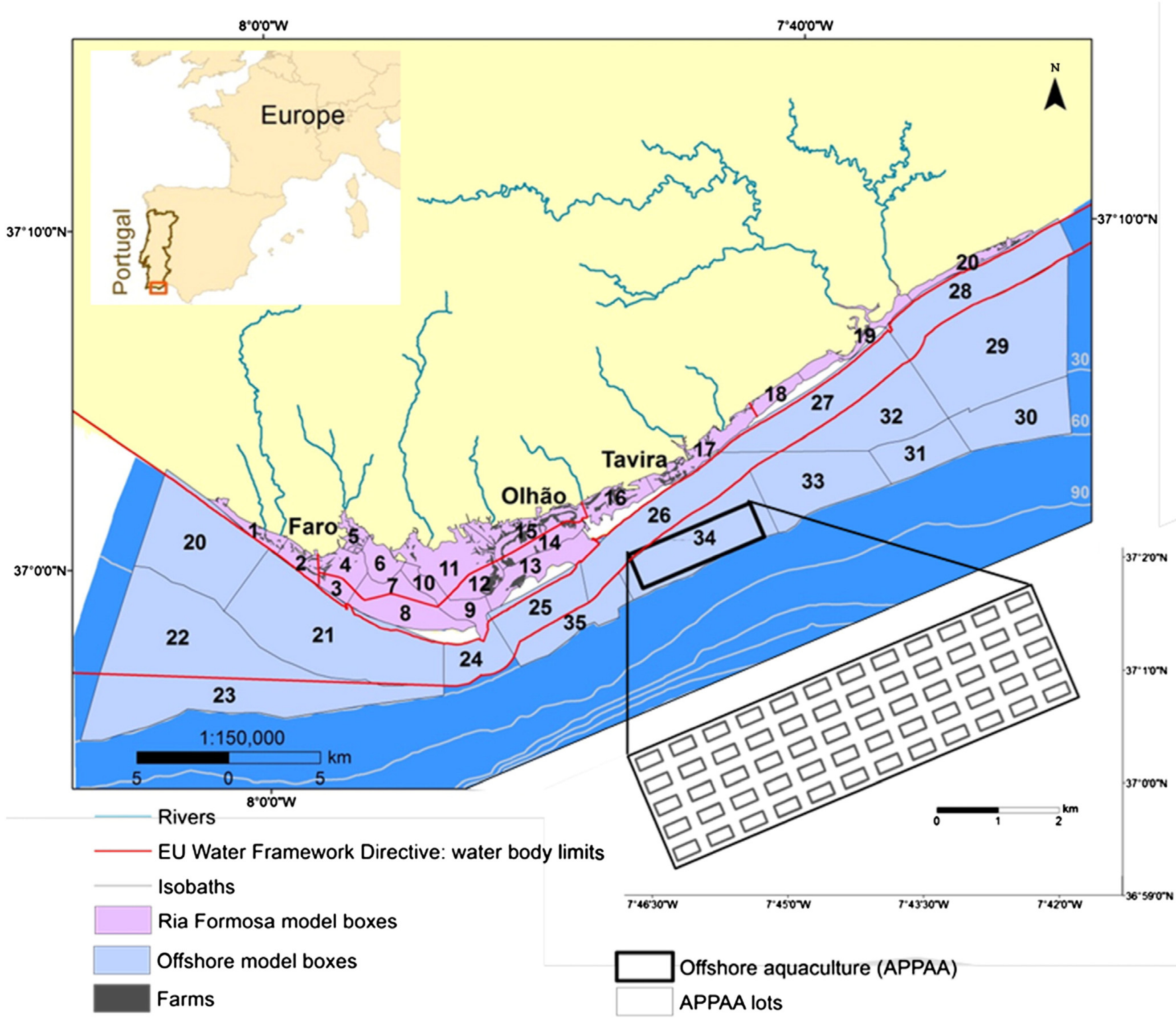

Fig. 2. Spatial domain for the modelling framework, including the catchment area, inshore and offshore boxes of the ecological model, and the 15 km^2 offshore aquaculture park, shown within box 34 of the model.

The Ria Formosa's morphological characteristics lead to a complex hydrodynamic response, mainly to the semi-diurnal, mesotidal forcing. Simulations with the Delft3D-FLOW model show that at the head of the main channels and in the tidal creeks the flushing is on the scale of weeks to months. By contrast, the model also shows that the tide is responsible for flushing times of 1 day to 1 week near the inlets and in the main central area between the Faro-Olhão and Armona inlets where an exchange of 50 to 75% of the total volume takes place each tidal cycle. An indirect calculation by Mudge et al. (2008) using salinity as a tracer gave similar results. The short water residence time inside the Ria means that the pelagic food supply for clams is largely driven by offshore production, where the combination of nutrient loading from the watershed and higher water residence times allow for phytoplankton blooms. At the shelf, the tide is less important and the main drivers are the wind and the thermohaline circulation, influenced to some extent by the mesoscale dynamics.

A vertical profile of chlorophyll over a clam bed (Ferreira et al., 2013) shows food depletion near the bed (Fig. 6).

Chlorophyll is higher during the flood tide, which suggests that the pelagic food supply originates mainly offshore and is advected into the Ria through tidal action. This is consistent with the short water residence time in the inshore area, which limits autochtonous phytoplankton growth (Ketchum, 1954). Resuspension of algae close to the bed only seems to occur at the beginning of the flood tide. Particulate organic matter shows a similar pattern. The concentration of microphytobenthos at the surface of the bed is high, with values of 4–8 μg g^{-1} (Brito et al., 2010). If we consider a penetration depth of 2 mm into the bed, and a sediment density of 2600 kg m^{-3}, the microphytobenthos concentration would be 20–40 mg m^{-2}, an order of magnitude higher than the concentration of phytoplankton (1–2 mg m^{-2}). In addition, not all the phytoplankton is accessible to the clams. It therefore seems reasonable to assume that microphytobenthos can be an important food source for the cultivated bivalves.

3.2. Offshore aquaculture park model

Shellfish production in monoculture for the offshore park as a whole was evaluated by means of a marginal analysis (Fig. 7, see e.g. Ferreira et al., 2009).

This shows a typical production function with diminishing returns (Jolly and Clonts, 1993), which allows prediction of the shellfish stocking density for profit maximisation, based on food availability, and input and

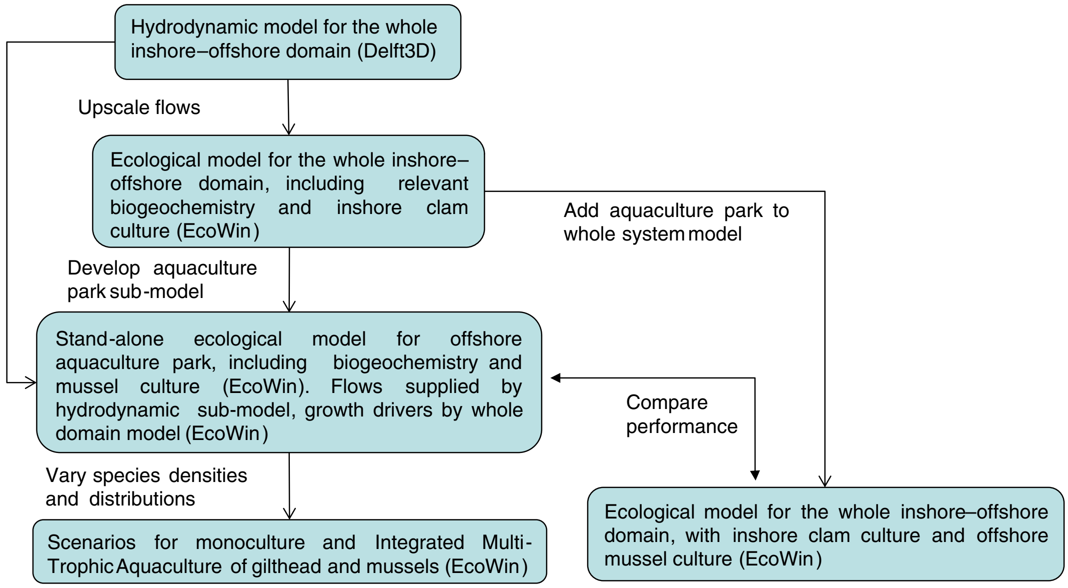

Fig. 3. Stepwise model development, illustrating the implementation of the standard ecosystem model for the inshore–offshore area, the standalone offshore aquaculture park model, and the combination of the two components.

output costs. This occurs for a marginal physical product (MPP) of 0.3, which corresponds to about 7500 individuals per m^2, and an average physical product of 5.5.

A detailed optimisation analysis combining different stocking densities (S) for the mussel leases (L) is not feasible, since it requires S^L model runs – for twenty leases, three combinations (not enough to

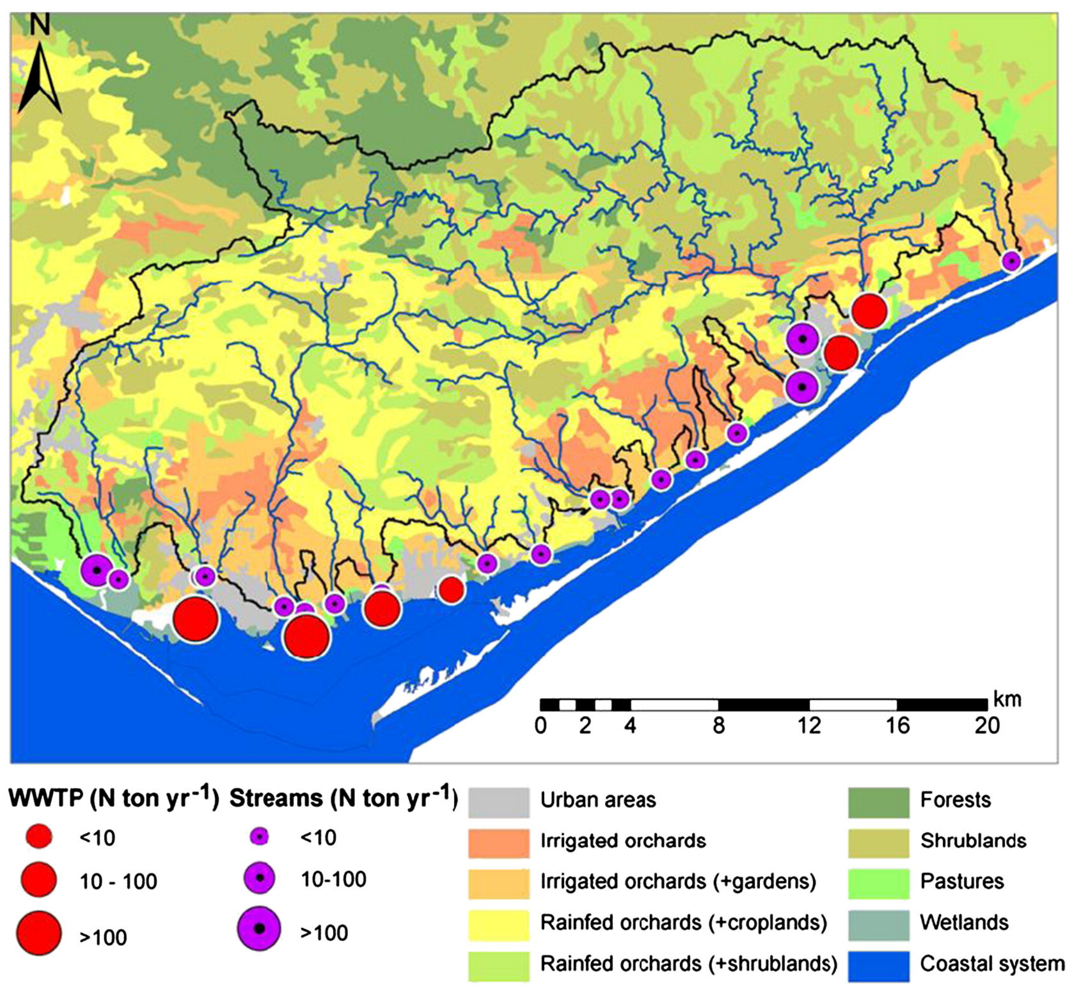

Fig. 4. Nutrient loading to the inshore area (Ria Formosa). The SWAT model results suggest that about half of the nitrogen load is from diffuse sources.

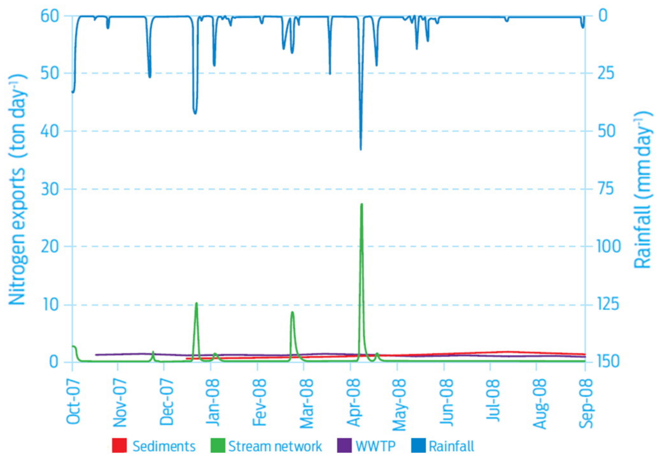

Fig. 5. Estimated daily nitrogen loads to the Ria Formosa from the catchment over the hydrological year 2007/2008.

generate a production function) would result in 3^{20} simulations. Alternative spatial layouts and finfish stocking densities would introduce additional complexity. A Monte Carlo approach where a family of curves is analysed to provide an approximation to optimised density and distribution is probably the best option.

A comparison of environmental performance of monoculture and IMTA is shown in Fig. 8. Particulate organic matter (POM) is used as an indicator of the role of filter feeders in mitigating the negative aspects of fed aquaculture due to excess feed and particulate waste.

The densities at which IMTA occurs in North America and Europe do not normally allow detection of concentration changes for POM or chlorophyll, but changes in material flux can be shown using models (Ferreira et al., 2012a, 2012b, 2012c). Only minor differences in POM can be seen in the present simulations, but the patterns observed are of interest.

Clockwise from the top left figure: the concentration of POM when all leases are empty decreases in the blue (mussel monoculture) leases, and increases in the yellow (finfish monoculture) leases, but also increases in the adjacent empty leases due to water circulation. The final scenario, combining finfish and shellfish in IMTA, illustrates the response in shellfish leases, where POM is recovered and enhances mussel production. The decline in POM is sharper at the western (left) boundary of the aquaculture park, since there is better growth in the outer shellfish leases, where there is less food depletion.

Models of this kind may be used to adjust both layout and density of different types of culture, in order to maximise yield and minimise negative externalities of finfish culture, bearing in mind the caveat mentioned above with respect to the combinatorial challenge of a detailed analysis.

There are significant challenges in running an aquaculture park of this nature, with respect to culture practice. For optimisation of both production and environmental effects, cultivation should run continuously, although the growth cycle is over twice as long for e.g. gilthead bream or sea bass, than it is for Mediterranean mussel. From a governance perspective, the all-in-all-out approach used in Norway (Ferreira et al., 2013), followed by a fallowing break, is highly recommended as a way to control disease (Werkman et al., 2011).

In practice, a business model that allocates leases to multiple users in a relatively confined area makes it challenging to enforce synchronized seeding and harvesting practices. Although aquaculture parks are appearing in various parts of the world, it remains unclear whether this is the best model for sustainable growth of offshore aquaculture.

3.3. Interactions between inshore and offshore aquaculture

The final set of simulations shows the potential interactions between inshore and offshore culture. When the 60 leases are active for mussel culture in the system-scale model (Fig. 9), there is a pronounced effect on inshore aquaculture. The annual harvest decrease of 120 tons of clams, about 3% of the total, has a financial impact of 1.2×10^6 €. This decrease, as suggested above, is believed to be driven by the depletion of food from offshore, which is removed by farmed mussels before the water enters the Ria Formosa on the flood tide.

The spatial impact of the offshore park is not equally felt within the Ria – the inshore area near the town of Olhão is the hardest hit, with a predicted 15% drop in production. Due to the characteristics of water circulation, clam production in the eastern and western edges of the inshore area appears to be largely unaffected.

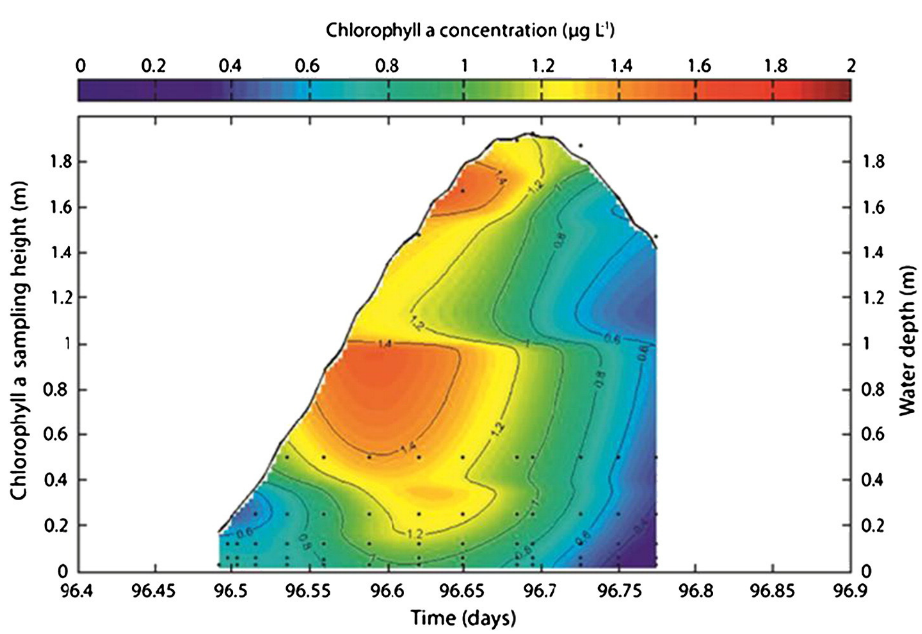

Fig. 6. Chlorophyll profile measured over a clam bed for a tidal cycle. Due to the short water residence time of the Ria Formosa, the concentration of pelagic algae that are part of the clam diet is significantly higher on the flood tide.

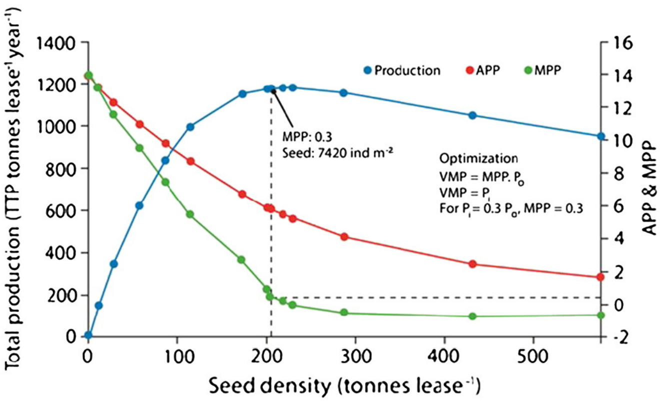

Fig. 7. Marginal analysis of mussel yield (21 mussel leases—see Fig. 2). MPP: Marginal Physical Product; APP: Average Physical Product.

The pattern of primary production over the modelled domain is unusual, since the inshore area outwells nutrients and acts as a net importer of organic material. By inserting a filter (the offshore aquaculture park) to this supply, there is a negative effect on clam production, and potentially also on wild fisheries.

The system-wide model predicts an annual mussel harvest of 13,000 tons. The yield obtained in the whole (inshore–offshore) system simulation is about 50% lower than that obtained with the aquaculture park model (Section 3.2) because the drivers imposed at the model boundaries are not constrained by food depletion due to mussel filtration within the aquaculture park. Similar results were obtained by Nunes et al. (2011) in Killary Harbour, where a ratio of 2 was observed between peaks of Total Physical Product (TPP) curves simulated by the FARM and EcoWin models.

The mussel crop has a much lower unit value than clams, but since the predicted harvest of mussels in the offshore park is much greater, the overall financial balance is positive. However, this comparison requires a deeper analysis both economically and socially because:

- Different stakeholders hold the rights to inshore and offshore aquaculture. The former leases are typically smallholdings, with areas as small as 0.4 ha, and are therefore highly sensitive to boundary conditions, including sediment erosion and accretion, whereas the larger offshore leases represent a broad-scale, capital-intensive business model;
- Estimates of financial trade-offs given herein are based on gross income – a full comparison would need to take into account a number of important factors, such as the amortization costs of offshore structures, shipping costs for delivery of mussels to port, and also the cost structure of the clam business, which is much more artisanal. One important difference is that for mussel culture there is no need for depuration, since farming takes place in offshore Class A waters (sensu Directive 2006/113/EEC).

The connectivity between the offshore park and the inshore clam areas also raises other questions such as disease spread (Salama and Murray, 2013). Fig. 10 shows results from a numerical simulation of the release of virus particles from the offshore area over a 6 day period.

As with production losses, the higher risk areas are the ones influenced by the inlet adjacent to the offshore park, but in this case the potential effect is greater in the leases nearest the barrier islands. The model also suggests that the spatial propagation of disease takes place more through water flowing outside of the barrier islands, and

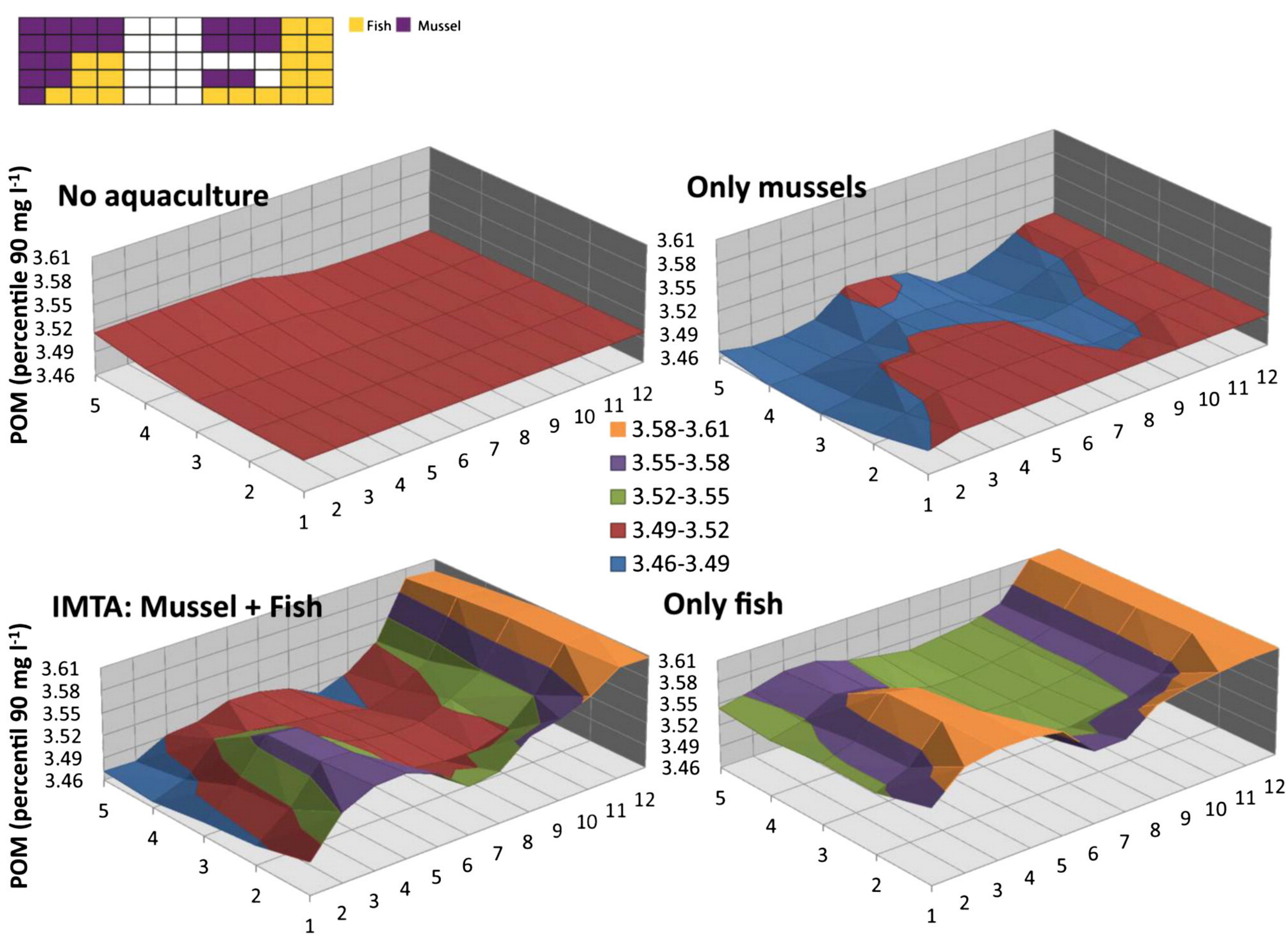

Fig. 8. Environmental performance of the offshore aquaculture park with various culture combinations (no culture, monoculture, IMTA).

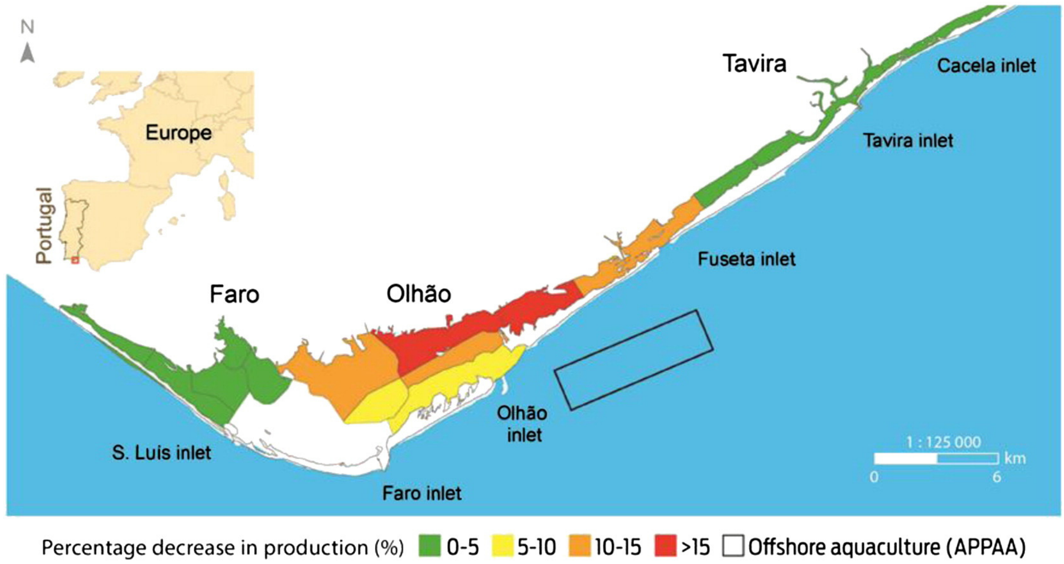

Fig. 9. Change in inshore production of the good clam *R. decussatus* with the addition of mussel culture in the offshore aquaculture park.

its re-entry on the flood through inlets further to the west. This is partly due to silting of the Ria's inner channels.

From a governance standpoint, in addition to the 'within-park' issues mentioned above, there are key aspects to be considered such as on-farm biosecurity (St-Hilaire et al., 2002) and species selection. Mussel diseases include Marteliosis (Cefas, 2013), caused by the protozoan *Martelia perfringens*, which can to some extent affect oysters cultivated within the Ria. Oyster culture is also being considered for the offshore aquaculture park, and the hydrodynamic connectivity (translated as risk in Fig. 10) could in this case be a bidirectional threat for contamination with *Perkinsus*.

In addition, major mussel fouling of fish cages has been observed within the Ria over the past year. This is a new phenomenon, which may be due to mussel seed released from the offshore park – it has resulted in damaged nets and conflicts among stakeholders.

The overarching lesson is that developments of this nature need to be well supported by planning that allows for sustainable growth, taking into account the multiple uses of the coastal zone.

4. Conclusions

The simulations presented in this work illustrate the value of a system-scale approach, rather than piecemeal planning which has often been characteristic of aquaculture development. By combining various types of models that work at different scales, and with different objectives, we can draw conclusions about production, environmental effects, and disease.

Coastal managers are interested in establishing the carrying capacity for a particular area. It may be relatively easy to flag when that capacity has been greatly exceeded, based on production (Raillard

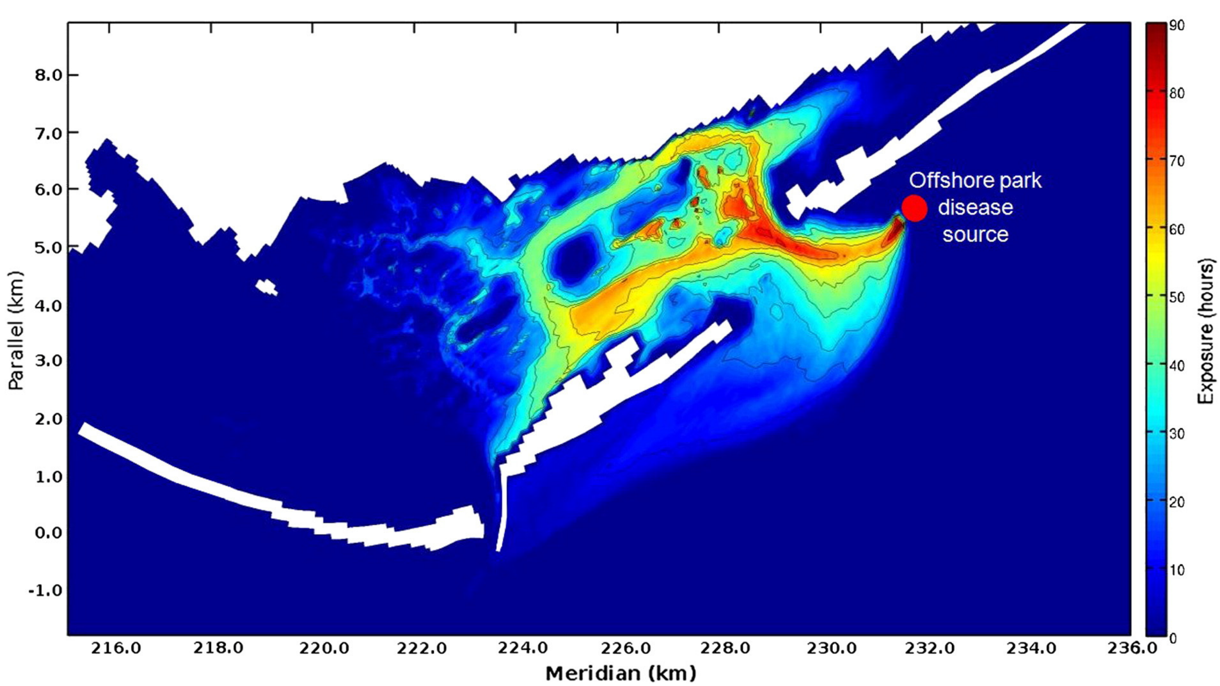

Fig. 10. Risk map of potential infection in inshore clam leases based on hydrodynamic connectivity, expressed as number of hours exposure to 0.5% of shedding concentration from the offshore area.

and Ménesguen, 1994), environmental (Ferreira et al., 2012c), or social (Byron et al., 2011) indicators, but the definition of a particular threshold is a very different proposition. Not only is carrying capacity a combination of the indicators referred (Inglis et al., 2000), to which governance should be added, but harmonization of multiple uses in time and space is fundamentally a collective choice (Olsen, 2003). For instance, license renewals might be inadvisable for a less productive area on the basis of carrying capacity simulations, but local communities and traditions may play a key role in defining the trade-offs. Models can be useful to the extent that they support the decision-making process.

The use of spatial planning tools such as Geographic Information Systems (GIS) for coastal systems, both within and beyond the limit of territorial waters, should be complemented by dynamic models that can quantify relative yields, because they incorporate elements of connectivity, transport of water properties, and ecological processes.

Furthermore, the explicit recognition (in mathematical terms) that the watershed component is coupled to the marine system, to the extent that nutrient management on land can potentially affect an offshore aquaculture park, extends the usefulness of this type of framework into the realm of the ecosystem approach to aquaculture.

There are two interesting challenges that stem from this work. The first is the legacy question, because the various component parts of this framework fall into the category of research models, which are not necessarily easy to use. It is therefore important that these integrated tools find downstream users who can amplify the connection to management, and to ordinary citizens, and provide feedback mechanisms.

Allied to this, the development and application cost may pose a challenge to emerging nations and increase the information divide. However, there is an ever-increasing availability of zero-cost modelling packages that address many of the issues discussed, and there are currently many freely accessible operational oceanography products (e.g. Kapetsky et al., 2013) that will assist in calibration and validation of models aiming to support the development of offshore aquaculture.

The continued use of such models will result in improved capacity building in many parts of the world, and to a more productive dialog between interested parties. This in turn will lead to better governance, based on mutual understanding of the trade-offs and compromises that form the essence of coastal management.

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