FORWARD

Framework for Ria Formosa
water quality, aquaculture,
& resource development

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FOREWORD

Over the last decade it has become apparent that the sustainability of aquaculture is a multifaceted question, with aspects that extend well beyond production, into the realms of ecology, governance, and social acceptance.

During the same period, there have been significant improvements in different kinds of mathematical models used for the assessment of some of the components of carrying capacity. Not only are the models themselves better, and easier to use, but the advent of distributed computing on mobile applications shows immense promise for broader access in the future.

In parallel, Europe and North America have taken stock of the fact that they now import the majority of their aquatic products from China, SE Asia, and South and Central America. A significant proportion of those products are derived from aquaculture. With wild fisheries flat-lining or contracting, aquaculture holds the promise of providing the marine and freshwater foods required for an expanding world population, set to reach nine billion by the year 2050.

Like many other activities, aquaculture has often developed unsustainably, to the extent that in Western nations there is significant public resistance to expansion. In many respects these nations import the fish and export both negative externalities and jobs—both exports are unsustainable.

In addition, balanced aquaculture activities can make an important contribution to integrated coastal zone management; top-down control by cultivated shellfish such as clams, oysters, and mussels has a direct positive effect on the symptoms of eutrophication, such as elevated algal biomass and low oxygen events. After several decades, costly source control of nutrient emissions is in some cases being shown to fall short of the promise of ecosystem restoration.

This book analyses these challenges for an ecosystem in southern Portugal, the Ria Formosa, where old meets new. Cultivation of shellfish has been practised for centuries, but a new management paradigm that accommodates multiple uses is required. These uses include tourism and marine protected areas, as well as development of offshore aquaculture parks, and many other activities.

The POLIS LITORAL Ria Formosa P6 plan (contract nº 101/10/CN003) provided funding for the FORWARD (Framework for Ria Formosa Water Quality, Aquaculture and Resource Development) project, and the outcomes of the work form the basis for this book. The work described herein has a strong quantitative component, but it recognizes the limitations of models in addressing a topic as complex as sustainable carrying capacity for aquaculture.

By comparison to ecosystems in the developing world, where there is often a paucity of the most basic data, the Ria Formosa may be considered to be well studied. Nevertheless,

data by itself is of little use—data is expensive, information is valuable.

Our aim was to use the range of tools at our disposal, both quantitative and qualitative, to provide a comprehensive assessment of the state and future of aquaculture in a very complex, fragile, and beautiful system. We hope that some of the lessons we learnt will be of use in other parts of the world, where farmers and managers struggle on a daily basis with the challenges of sustainability.

The road from data to knowledge is inextricably linked to information, and the publication of the FORWARD book in both Portuguese and English makes this information more broadly accessible, for example in South and Central America, and in large parts of sub-Saharan Africa. The tools of sustainability assessment in aquaculture are not a possession of wealthy nations, but a common good that must be used for the benefit of all, so that the production divide is not accompanied by an ever-widening gap in information.

FORWARD TEAM

The FORWARD team, together with IPIMAR colleagues and stakeholder representatives.

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TABLE OF
CONTENTS

EXECUTIVE SUMMARY

The FORWARD project (Framework for Ria Formosa Water Quality, Aquaculture, and Resource Development) was executed in order to analyse shellfish and finfish aquaculture in the Ria Formosa, to gain a better understanding of the interactions between aquaculture and environment, and to promote sustainable development of aquaculture.

provide an example of the state of the art in integrated management of coastal systems.

The work described in the FORWARD book addresses the prospects for sustainable development of aquaculture in the Ria Formosa, an area that has been used for wild shellfish harvest since the days of the occupation of the Iberian

FIGURE 1 — Capture fisheries for human consumption and aquaculture

Capture fisheries for human consumption

September 2011

$r^2 = 0.99$, p<0.01

Aquaculture

Live weight (10^6 tonnes per year)

Year

■ ■ Data points ·········· Extrapolation
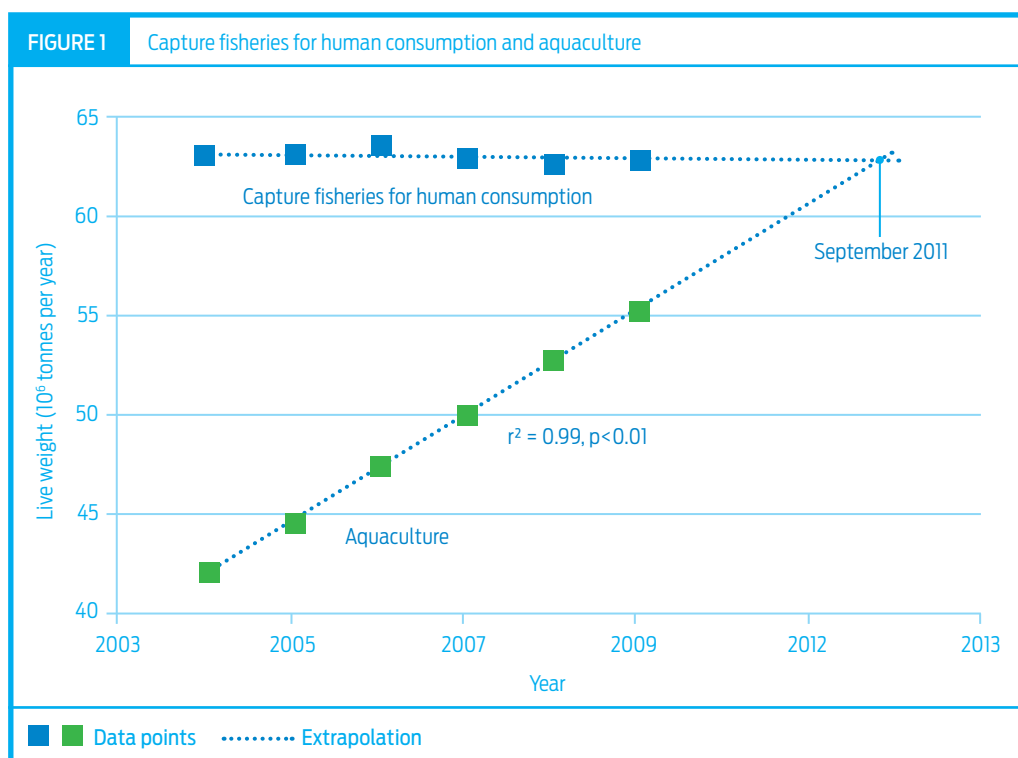
The FORWARD book was written in both English and Portuguese in order to ensure a broad dissemination, illustrating the commitment of the Portuguese authorities in promoting the sustainable use of Ria Formosa, and

Peninsula by the Moors, more than thirteen hundred years ago, and for clam cultivation for over the last two centuries (Figure 3). Twenty-three recommendations are made in this executive summary, each one based on a specific finding.

AQUACULTURE IN EUROPE AND THE WORLD

Data from the most recent FAO report on fisheries and aquaculture, published in 2010, define a milestone in the relationship between the two activities: aquaculture, with an annual production of about sixty million tonnes, is now equal in volume to capture fisheries; furthermore, future trends are an increase in aquaculture and a stabilisation or reduction of wild fisheries.

The data projection in Figure 1 indicates that this point will have been reached in September 2011, taking into account the fraction of fish used for human consumption. Part of the wild catch (25-30%) is used for other purposes, including production of feed for aquaculture. In agriculture this critical point, i.e. where farming overtook hunter-gathering, was reached 10 000 years ago in the Neolithic Period.

CARRYING CAPACITY AND THE ECOSYSTEM APPROACH

The concept of carrying capacity in aquaculture, based on four pillars of sustainability (Figure 2), has been adapted to include governance, considered more relevant than the physical element, which in many respects is encapsulated in the production component.

Governance, on the other hand, is clearly missing from the original model and the quality of balanced regulation, stakeholder involvement, and community-based management often constitutes the difference between sustainable aquaculture and an environmental time bomb.

The bulk of the projected thirty million tonnes y^{-1} of additional aquatic products required to feed the planet by the year 2050, when the world population is expected to reach nine billion, will undoubtedly be cultivated

FIGURE 2 The relative importance of the four pillars of carrying capacity

US, Europe, Canada

Highest

Types of carrying capacity

Production

Ecological

Governance

Social

Southeast Asia, China

Highest

Figure 3. The Good Clam, shown here at a commercial size of 35 mm.

in developing countries, principally in Asia, but also in South America, and potentially in Africa.

In Europe, annual growth of aquaculture has declined to 1%, partly because of market factors, but also because the industry is subject to stringent regulation and sustainable development is a major consideration. Recent environmental legislation, such as the European Union's Water Framework Directive (WFD 2000/60/EC) and Marine Strategy Framework Directive (MSFD 2008/56/EC) has implicitly promoted the three objectives of the FAO Ecosystem Approach to Aquaculture (EAA), namely (i) human well-being; (ii) ecological well-being; and (iii) multisectorial integration.

MODELLING FRAMEWORK AND SUSTAINABILITY ANALYSIS

Two of the pillars illustrated in Figure 2, production and ecology, are amenable to mathematical modeling, and two are not. For the former, the FORWARD team combined different mathematical models into a framework for analysing sustainability (Figure 4), and this framework was subsequently applied to a range of issues, as described later in this book.

Issues related to disease, which fall squarely between production and ecology, and which are extremely difficult to model, are a huge challenge in aquaculture, and often include a significant element of poor governance, such as relaying of infected animals to hitherto uncontaminated areas.

Finding: At present, two major components of carrying capacity, the social and governance aspects (Figure 2), are not amenable to mathematical modeling—they are nevertheless fundamental for aquaculture management. The importance of these for sustainable development of aquaculture in the Ria Formosa became evident during the first half of the two year FORWARD project—they may well correspond to over 50% of the problem.

Recommendation: Stakeholder dialogue, understanding of terms and concepts, and the simple fact that opinions can be voiced during the decision-making process, are major contributors to generate consensus. Appropriate governance plays a major role in a sustainable future for aquaculture in the Ria Formosa.

The social and governance issues identified are described below, together with proposals for improved management.

The final section of this summary provides an overview of the results for the simulation models applied in FORWARD. These can be used to inform that discussion, by e.g. providing quantitative data on development scenarios, but social positions often have a strong emotional component. The application of simulation models *per se* is necessary but not sufficient to address the question as a whole.

PRODUCTION AND VALUE OF AQUACULTURE

Finding: Estimates vary on the current production of the main cultivated species, the Algarve or Good Clam, *Ruditapes decussatus*. The landings data range from official estimates of about 2000 tonnes per year to unofficial figures of more than double that number – five thousand tonnes is often referred. Production can also be calculated from the total leased area using a Geographic Information System,

FIGURE 4 FORWARD modelling framework.
Combination of different models and other approaches for management support.
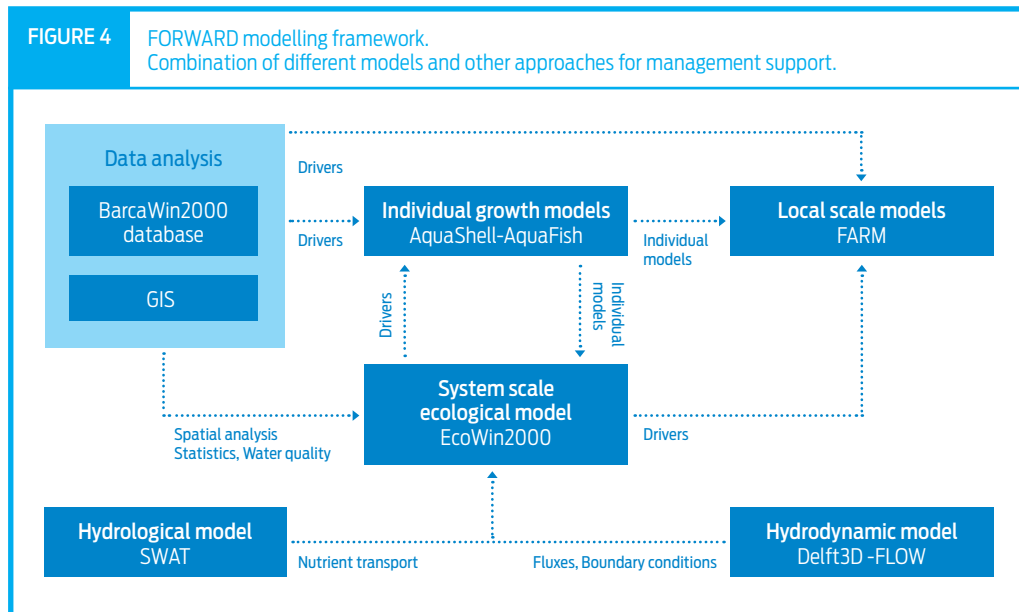
FIGURE 5   Snapshot of GIS for lease management

🟩 Example lease. Number: 735 / Concession: 704/90 / Area (ha): 0.4
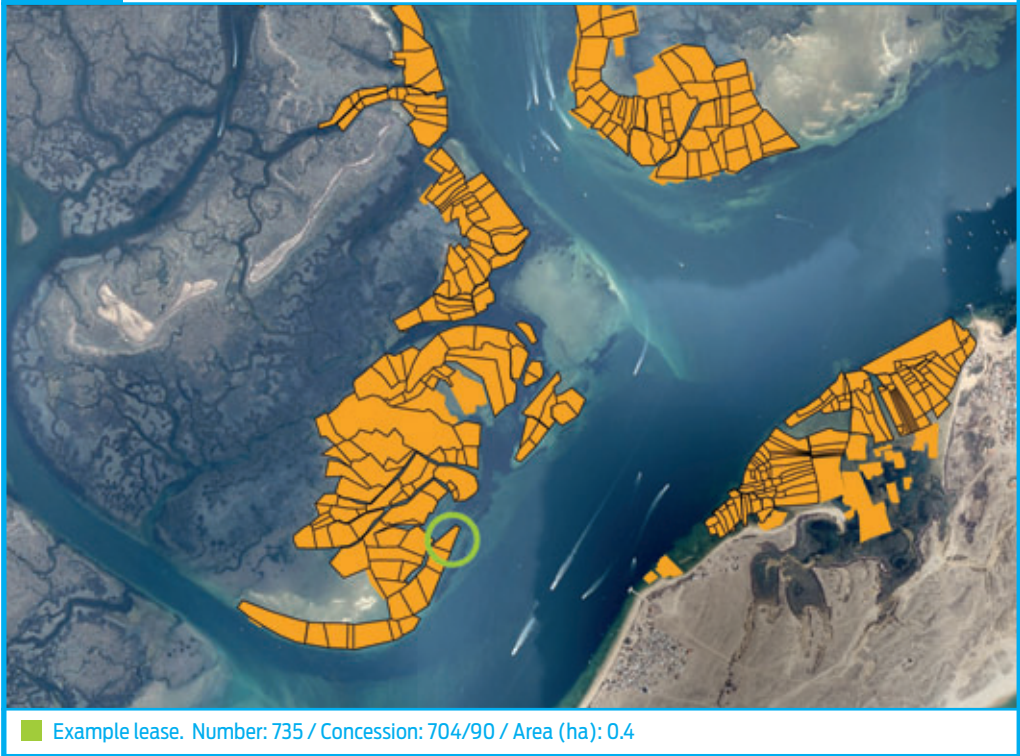
or GIS (Figure 5), and simulated by means of ecological models.

The Good Clam is a high value product, in contrast to species such as Manila clam (*Ruditapes philippinarum*), fetching a minimum farmgate price of 10 € kg⁻¹. Consequently, the annual first sale revenue determined for a clam production of 5000 tonnes per year is 50 million euros. Discussions with stakeholder groups during the project suggested that anywhere between 20 000 and 40 000 people may be actively involved in the industry, which would correspond to a gross annual income of 1250-2500 € per capita, which is not credible.

Using an alternative approach, the average wage per tide is about 50 € (Table 17), corresponding to monthly earnings of 750-1000 € per capita. A calculation with those numbers places the labour force at between 4000 and 6000 people. The combined population of the area (Faro, Olhão, and Tavira) is about 125 000, so about 4% of the workforce might be directly employed in clam aquaculture, and the first sale revenue corresponds to 2.5-7.5% of the local GDP, depending on the landings estimate used.

Recommendation: An improved socio-economic analysis is important in order to better determine the role of clam aquaculture, both in terms of the people involved and economic relevance, including employment multipliers, markets, etc. It is also important to analyse the overall GDP of the Ria Formosa, including

FIGURE 6 Partitioning of GDP by different types of activities (courtesy Patrick Marshall)

Resource Extraction & Harvest	Manufacturing & Processing	Retail Service Commerce	Government	Non Government (NGO's)
Harvest it	Make it	Service it	Regulate it	Volunteer for it

capture fisheries, aquaculture, salt extraction, and tourism. An analysis by sector (Figure 6) would be extremely useful.

Finding: According to the EU Shellfish Waters Directive (2006/113/EEC), the waters of the Ria Formosa are considered as Class B; as such, shellfish products from the Ria Formosa require additional cleaning before they can be marketed. At present, six depuration plants exist, often playing an intermediary role, which may be a barrier with respect to product sale, since the depuration certificate is an essential part of the sale procedure.

Recommendation: The role of depuration centers needs to be clarified; depuration will become unnecessary as the water quality of the Ria Formosa improves to reach Class A, but the depuration certificate can reassure the consumer as an additional health safeguard. The public administration needs to ensure that clam and oyster farmers have unrestricted access to depuration facilities at a fair price, and are in no way constrained to sell their product to depuration plants.

Finding: Although the 'Good', or Algarve clams, are a high value product, there is no particular recognition of the origin of the clams, such as exists for wine regions throughout Europe, and food products such as cheese.

Recommendation: A Ria Formosa brand should be promoted, perhaps as a sub-set of the Algarve brand name. Branding should be shown prominently on packaging, with an appropriate logo. Europe cannot compete on volume in the aquaculture market, so regional high value products must be placed by under-scoring their origin, quality standards, and concerns with respect to sustainability.

CULTURE PRACTICE

Finding: Many growers lease small farms, which is a management challenge. Some of the culture practices that are considered undesirable with respect to natural values are associated to the perception by farmers that each lease is an area that must be preserved spatially, and where production must be maximized—the lease value is considered to be dependent on these two factors. Consequently, plots are delimited by means of dividing markers such as bricks, ironwork or other objects. These separators play a dual role in clearly demarcating leases and preventing erosion.

Any tide pools within the leases are considered undesirable by the growers. These pools are formed naturally due to the irregular substrate, but since farmers wish to maximise the culture area, and the pools can easily become hypoxic or anoxic at low water, leading to mass mortality of shellfish, levelling is common, with drainage channels dug in the mud for outflow.

Recommendation: Restructuring of licensing scheme, to reduce the number of leases and increase unit size. This should be done gradually as leases expire, and be fully discussed with industry associations. Larger leases will be less vulnerable to marginal erosion with respect to the total lease area, and substrate losses in one part of the lease may be compensated by sediment deposition in other parts of the lease. This will remove the requirement for the use of extraneous objects such as bricks to attempt to consolidate substrate. Since these objects are also used to delimit small plots, this will also become unnecessary. The levelling of tide pools in these larger leases should be discouraged, since they are part of the natural ecosystem. Larger leases will reduce capital costs, and potentially allow an increased degree of mechanization, lowering labour costs. A reduction in the number of stakeholders may also improve the effectiveness of collective decision-making.

Finding: Mixed cohort plots are standard culture practice. This has several consequences, including (i) constant re-working of the sediment by growers; (ii) reduced possibilities for mechanized harvesting; (iii) mortality of larger, more fragile animals, in the post-spawning period can cause the death of later year classes (smaller animals) due to organic decomposition. There are diverging opinions on combined culture of year classes (up to three year classes). For instance in Puget Sound, USA, some farmers prefer co-cultivation, arguing that some of the elimination products from larger Manila clams are used as food for the smaller animals. Others, however, use mechanized harvest to reduce labour costs and increase profits.

Recommendation: Farmers should be encouraged to experiment with alternative culture strategies, including mechanized harvest. This should be accompanied by extension workers from fisheries centres, and be tested in a precautionary manner. In order to explore this possibility, the legislation must be adapted appropriately, and leases cannot be below a certain size. Half a hectare (5000 m^2) would seem to be a minimum dimension for a part of a plot to be grown in year class strips.

Finding: Clam culture practices in the Ria Formosa vary widely, and the whole industry would benefit from a more modern approach to cultivation, along the lines of the requirements set down by retailers such as Walmart or Wholefoods. The producer associations, local managers, and government agencies are keen to establish a certification program for the fishery.

Recommendation: The FORWARD project researched the various options, and proposed that Global GAP should be selected as a certification body. This was based on the type of product offering, pricing, and accessibility. A website was registered and developed (http://goodclam.org/) to allow producer associations to complete and submit certification documents. A subsequent inspection by the certification agency will identify shortcomings, and after these are addressed, it will be possible to certify a culture area. Growers associations should prepare for certification, driving their members to more sustainable cultivation practices. Individual growers will benefit by commanding a higher product price, and the whole community will benefit from increased recognition of quality, brand certification, and a more significant participation in the value chain. The industry needs to be stimulated to achieve this, shifting from traditional practices; this is an important extension role for local fisheries agencies.

Finding: Anecdotal evidence was obtained in FORWARD that oyster culture in some areas of the Ria Formosa initially takes place on trestles, until the animals are around 3 cm long. Following that stage, the oysters are placed on the sediment for growout. Farmers reported that (i) oyster growth is far slower if the animals remain on trestles as they increase in size; (ii) clam culture involves appropriate preparation of the sediment, which is not ready for planting until a few weeks have elapsed, and it has changed in colour.

In both cases, this suggests that an appropriate benthic food supply is required for successful growth. Microphytobenthos concentrations are high in the tidal flats where aquaculture takes place—over 200 mg chlorophyll m^{-2}, whereas pelagic algae are in the range of 0-1 mg chlorophyll m^{-3}. It appears likely, given these food concentrations, that microphytobenthos is an important food source for the cultivated shellfish.

Recommendation: Although several published studies exist in the Ria Formosa on microphytobenthos dynamics, the focus has been on utilization of nutrients, and on eutrophication symptoms. In parallel, there is some stable isotope work on algal food sources for bivalves. Further research work is needed, focusing specifically on the food source issue, in order to clarify the role of pelagic and benthic algae as drivers of clam and oyster growth.

SEED, JUVENILES, AND DISEASE

Finding: Sources of seed are an issue for both clam and oyster culture. Natural seed beds exist for the Good Clam, but at present no hatchery or nursery facilities are available. Oyster seed in particular is supplied from hatcheries in France, Ireland, and elsewhere. There are presently no estimates of density or stock in the natural clam seed beds of the Ria, making it impossible to assess whether collection is sustainable.

Recommendation: Improve access to seed and juveniles, through the development of more flexible guidelines associated to better enforcement.

Evaluate the stocking density and area of natural seed beds, in order to provide guidelines for sustainable seed collection.

Hatcheries are expensive, of the order of 100 000-1 000 000 €, and can be a commercial risk when natural recruitment is high, unless there is a clear downstream market for export of hatchery seed to other areas. Both public and private funding models have been used successfully, and an economic feasibility study, considering needs, markets, and financing, should be carried out.

Figure 7. FLUPSY operated by Taylor Shellfish Ltd., Shelton, Washington, USA.

Nurseries, on the other hand, are a much lower expense (10 000-100 000 €), and enable the purchase of smaller, and therefore cheaper, seed, which is then reared and sold on for growout. In the United States, floating upweller systems, or FLUPSYs (Figure 7), have been highly successful for such a purpose.

Finding: Import of oyster seed from contaminated areas may lead to the emergence of diseases such as *Herpes*.

Recommendation:
Establishment of strict veterinarian controls and traceability to avoid further proliferation of shellfish diseases due to import of contaminated seed. Bring the industry together in terms of disease understanding and approaches. An expert group should be established to advise on disease, including fisheries centres and veterinary professionals. An integrated, transparent disease monitoring scheme that involves stakeholders should be established. The use of hatchery reared/safe seed needs to be standard procedure. Research into pathogen management should be developed.

CLAM MORTALITY

Farmers often shorten clam production due to mortality issues, limiting the cycle to a maximum of two summer periods, thereby losing the added value of larger animals (20-30 g live weight) harvestable only in third year. The mortality may be due to a number of reasons, most probably in combination, which have not to date been systematically analysed.

Finding: High summer mortality is common. A combination of low dissolved oxygen in hotter months, loss of condition due to spawning, and stronger symptoms of gill disease (dermo) due to the protozoan pathogen *Perkinsus marinus* apparently combine to cause high mortality. It is possible that an increase in the height of clam beds, due to sediment addition, may also contribute to higher mortality, due to an increased exposure period at low tide.

Recommendation: Regular analysis of timing and spatial scale of mortality, to build up a multi-year (decadal) pattern of occurrence. Pre, during, and post-mortality analysis of temperature, dissolved oxygen, physiological status (gonad maturation and spawning) and *Perkinsus* levels. Study of correlations, trends, and interdependencies, and development of early warning monitoring systems and predictive models to provide advice to farmers, and training to the grower associations. Such a system should be web-based, and not necessarily free of cost. This will allow for early harvest and reduction of stocking density to avoid positive feedback of hypoxia due to decomposing organic material from dead animals. Comparative study of mortality in clam beds located at different heights above datum.

Finding: Excessive growth of opportunistic seaweeds such as *Ulva*, and seagrasses such as *Zostera*, can severely reduce dissolved oxygen concentrations during night-time low tides. Plant growth is stimulated by three factors: (i) the existence of suitable substrate, such as the gravel dumped onto the lease areas to stabilise sediment; (ii) ammonia released by clam excretion, and dissolved nutrients released by the sediment; (iii) optimal light conditions, particularly over the ebb. Mortality of both clams and plants occurs through oxygen depletion from the organic decomposition of either, or from smothering.

Recommendation: Regular mechanical mulching should be implemented, particularly in periods of peak fouling. For *Zostera*, removal should be analysed on the basis of the conservation status of specific species. Application of artificial substrates such as gravel should be discouraged, partly by extension work to illustrate their potential effects as nucleii for plant growth. Some of the issues described earlier related to lease size are a driver for the application of gravel and other materials.

Finding: With respect to pollution, growers are mainly concerned with faecal contamination and organic loads. There is a perception that lack of sewage treatment and irregular operation of wastewater treatment plants (WWTP) are the main sources of pollution. However, approximately 50% of the nitrogen load that reaches the lagoon via the watershed is due to diffuse pollution, i.e. a decrease in loading cannot be achieved through wastewater treatment plants. The same applies (qualitatively) to the loading of enteric microorganisms, which have both animal and human sources.

During periods of high rainfall, which occur sporadically, accidental sewage overflow, usually linked to stormwaters, may occur. Concurrently, increased runoff is directed into the water body. Given the torrential nature of such events, and the rarity of occurrence, clam or oyster mortality would be most likely be due to a short-term salinity drop. This is however difficult to observe. Given that such events occur infrequently, and are confined to autumn and winter months, it is highly unlikely that cultivated animals will die from hypoxia associated to organic enrichment or nutrient discharges. It is however highly probable that elevated microbial contamination of oysters and clams will occur over such periods.

Recommendation: Identification of mortality episodes during/after periods of high

precipitation. Conditioning or interdiction of harvest during and after high rainfall events and storms, or additional depuration, to ensure microbiological quality is adequate. Use of appropriate microbiological indicators to distinguish between point and diffuse sources, in order to determine appropriate management actions. Candidate microorganisms might include bovine enteroviruses (BEV), coupled with more sophisticated approaches such as antibiotic resistance profiles for faecal streptococci and faecal coliforms.

On the basis of the partitioning between point and diffuse sources, remedial action may be optimised, focusing more on improved agricultural practices.

FIELD AND MODELLING STUDIES IN FORWARD

The last part of this chapter identifies the main outcomes of the application of various types of mathematical models. With reference to Figure 4, we examine findings and recommendations from the models at both system and local scales, taking into account the catchment, Ria Formosa area, and offshore region.

Local scale processes

The physical and biological processes occurring at the farm scale, close to the clam beds, together determine the conditions experienced by the cultivated animals, particularly regarding food availability. A number of experiments were carried out to study these processes.

Finding: Shellfish density may be too high for the low concentration of food in the water column, particularly during the ebb. Food availability over the clam beds increases during the flood tide and decreases during the ebb, when the water previously filtered by the clams again flows over the lease area. No differences in food availability were detected between leases that apply gravel and those that do not.

Nutrient discharges to the Ria Formosa do not lead to high phytoplankton biomasses within the Ria, because the water residence time is too short for bloom formation. The effects of nutrient discharge on primary production are threefold: (i) export of dissolved nutrients to the adjacent coastal water, promoting offshore phytoplankton growth. That phytoplankton is advected into the Ria on the flood tide, and becomes a food source for the bivalves; (ii) blooms of opportunistic macroalgae such as *Ulva*, which are attached to the substrate and therefore unaffected by the short water residence time; (iii) development of micro-phytobenthos in intertidal areas, including clam beds. Since these algae are buried in the sediment, they are much less sensitive to the short residence time. The high concentrations referred suggest they may be an important food source for the shellfish.

Recommendation: Based on model results, experiments should be conducted in selected leases, to assess the effects of food supply on clam production and mortality. These experiments should consider different age classes (cohorts) and be extended over one year, to include the summer period when the animals are most fragile.

Watershed loads

The Ria Formosa watershed is a source of nutrients for the coastal system, which come mainly from anthropogenic sources. Loads can be point-source (WWTP) and diffuse (agricultural fertilization). The amount of nutrients and time period when they enter the Ria may have consequences for aquaculture activities.

Finding: the main nutrient sources for the Ria are, in equal parts, loads from WWTP (45% N, 32% P) and diffuse loads from agricultural fertilization (55% N, 68% P). The WWTP network has experienced significant improvements and can be considered adequate. Part of the sediment-source loads may come from coastal aquifers, which are highly contaminated by agricultural activities (41% N, 47% P). The associated processes are poorly understood. Streamflow loads (14% N, 21% P) occur over restricted time periods, following rainstorms causing high streamflow rates, during which they become the dominant source of nutrients.

Recommendation: the focus of studies and controls on watershed loads should move from WWTP to agricultural sources. There is still insufficient knowledge on diffuse contamination processes, and more information is required, particularly streamflow nutrient concentration measurements in peak flow periods, and studies on aquifer contamination and coastal interaction processes.

Water column transport and connectivity

The water exchange between the Ria Formosa and the ocean and the connectivity between regions within the lagoon affects ecosystem health parameters such as oxygen concentration and shellfish food availability. The 3-dimensional hydrodynamic modelling approach included for the first time the effect of the inner continental shelf circulation in the connectivity between the ocean and the lagoon and between the central and eastern cells of the lagoon.

Finding: High freshwater runoff and east winds transport water over the inner continental shelf from the eastern cell of the lagoon to the region of influence of the western cell. In east wind conditions, complete mixing of the

water column was found as far as the 20 m isobath, creating the conditions for higher percentage of re-incorporation of previously flushed lagoon water and consequently longer flushing times.

Recommendation: The bathymetry used for the three-dimensional model was the best available to the FORWARD project, but given the nature of sediment movement within the Ria Formosa, the use of an updated bathymetry for simulating water circulation is highly important. Financial provisions should be set aside for a regular update of the bathymetry of the Ria, performed by an accredited agency such as the Portuguese Hydrographic Institute. The costs are of the order of 500 000 €, and if a ten year amortization period is considered, this requires a multi-year annual appropriation of 50 000 € (Table 20). This is trivial (0.1%) in the context of a 50 million € per year aquaculture industry.

Finding: The different sections of the Ria Formosa are connected through the continental shelf, even though internal connectivity is limited due to silting. The residence time of water in the inner shelf increases under specific river flow and wind conditions.

Recommendation: These two aspects make it important to conduct detailed water circulation studies concerning the pathogen spread among shellfish aquaculture sites within the Ria, as well as between those areas and sensitive natural habitats offshore, including nursery areas and natural bivalve seed beds.

Ecological modelling

The EcoWin2000 ecological model was applied to a broad area, including the Ria Formosa and adjacent shelf. The model domain was divided into 35 boxes (Figure 8). Outputs from the watershed and circulation

FIGURE 8   Division of the system-scale modelling domain into 35 boxes, using criteria such as aquaculture, marine spatial planning, and EU legislation

Ria Formosa model boxes   Offshore model boxes   Offshore aquaculture (APPAA)
EU Water Framework Directive: water body limits   Isobaths
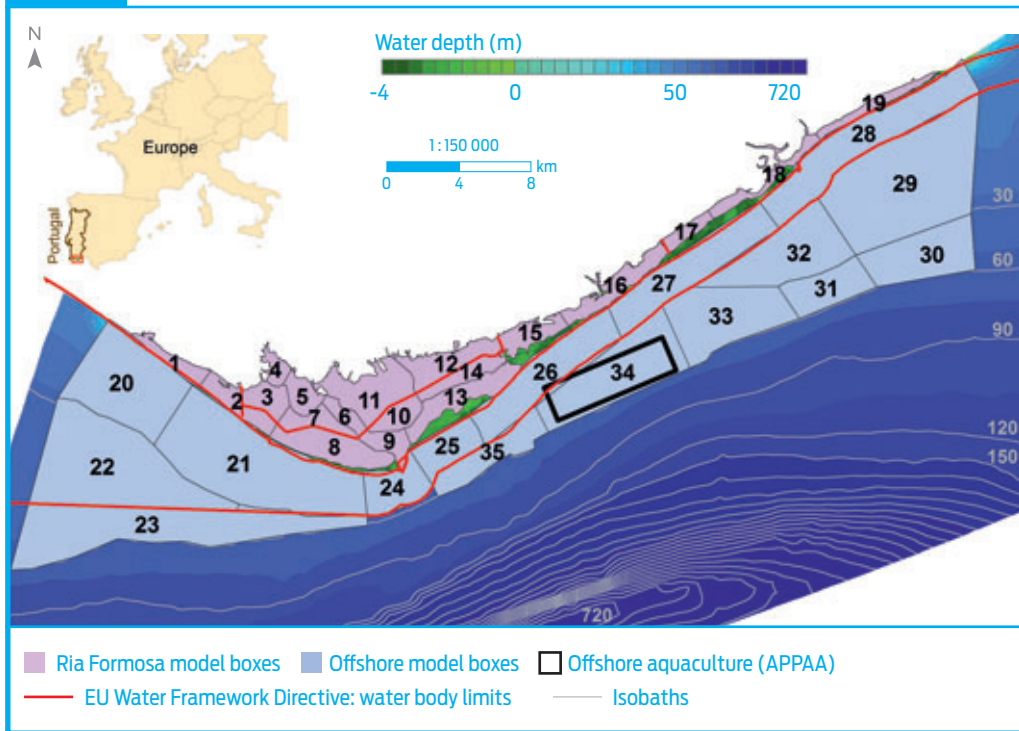
models were combined with environmental data, and individual shellfish and finfish growth models, in order to examine the general ecological behaviour of the area.

In parallel, local scale models were developed to analyse aquaculture at the scale of the existing leases. The complementary use of different models provides a range of tools to analyse different problems (Figure 4), and to deal with different time and space scales.

Individual growth models were developed for two species of shellfish cultivated within the Ria Formosa, the "Good", or "Algarve" clam *Ruditapes decussatus*, and Pacific

oyster *Crassostrea gigas*. The latter is grown in mixed culture with the Portuguese oyster *C. Angulata*, and although the local species has slower growth, it was not possible to develop species-specific growth data for modelling—in FORWARD both oyster species use the same model. In parallel, a growth model from the Mediterranean mussel, *Mytilus galloprovincialis*, was developed, since it is a species of potential relevance in the offshore culture area of Armona (APPAA). All these models are based on the AquaShell framework. Figure 9 shows a simulation of individual growth for Mediterranean mussel, for a culture period starting at the end of March and lasting just over a year. The environmental drivers for the simulation of growth are taken from the fourth

FIGURE 9   Growth of Mediterranean mussel in the Armona offshore aquaculture area. AquaShell individual weight
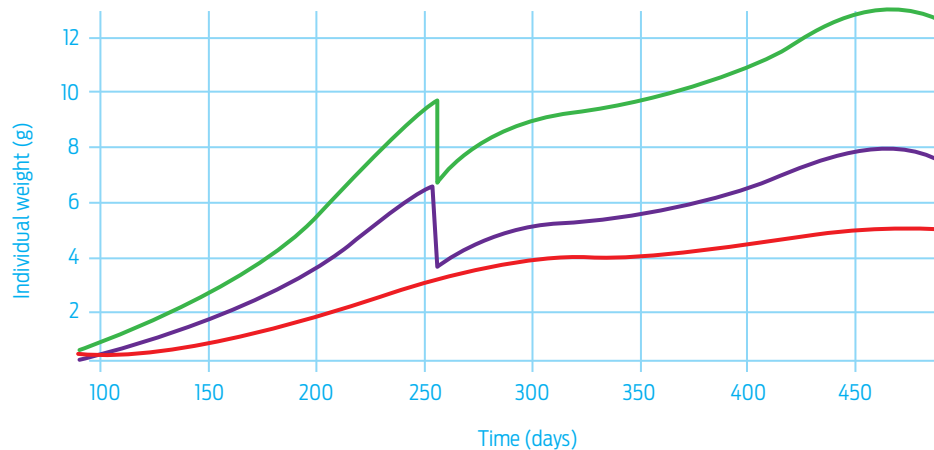
■ Total fresh weight   ■ Tissue wet weight   ■ Shell wet weight

TABLE 1	Mass balance for growth of one mussel to harvestable size (6cm)	
Parameter (units)		**Value**
Net biomass production (g live weight)		12
Clearance (m³)		29.7
Phytoplankton removal (mg chl m⁻³)		21
Detrital particulate organic matter (POM) removal (g m⁻³)		122
Total POM removal (g m⁻³)		125
Spawning losses (g POM m⁻³)		0.5
POM biodeposition (g m⁻³)		50
Ammonia excretion (µM m⁻³)		11 946
* POM: particulate organic matter		

year of the system-scale ecological model, considering full-scale clam culture in the inshore waters of the Ria Formosa.

The individual growth model also provides a full description of environmental effects (Table 1), which is translated in the upscaled system and local-scale models to analyse the impact of different types, areas, and practices of aquaculture.

A similar approach was taken for finfish, in particular for the gilthead sea bream *Sparus aurata*. This species is of local importance both for the wild fishery and in cultivation. Some onshore pond culture exists, although

there are stakeholder conflicts with respect to effluent discharge to the Ria, and licensing is very limited. Additionally, some of the land-based gilthead farms have closed due to competition from fish cultivated in the eastern Mediterranean, an area currently producing almost 130 000 tonnes per year.

System-scale models

Finding: The EcoWin2000 (E2K) ecological model, was set up and validated for standard conditions, a total clam harvest of about 2 300 tonnes per year. There is a wide variation in individual clam growth, and in the yield per unit area within the Ria Formosa. The best return on investment, as determined from the Average Physical Product (APP), is in the eastern part of the system, followed by the central area near the Armona inlet (Fortaleza) and by the Faro area. Simulations were made where the food available included not only the algae in the water column but also the microphytobenthos—a very conservative addition increases the annual clam harvest to 6700 tonnes. It is perfectly reasonable to accept values of double that tonnage, considering the microphytobenthos concentrations measured in the Ria Formosa.

Recommendation: Once set up, the E2K model is simple (Excel-like) and fast (about 15 minutes for 10 years) to run. Local managers should be trained in its operation, with the aim of testing various alternatives to cultivation, including reduction of seed density in areas of lower yield. As referred above, it is fundamental to study the role of microphytobenthos as a source of food for clams and oysters in order to optimise the application of E2K.

Finding: A generic simulation of mussel culture for the APPAA offshore aquaculture area returns a harvest of almost 13 000 tonnes per year. This suggests that shellfish aquaculture

appears to be feasible, at least from the point of view of growth.

Recommendation: A detailed application of the ecological model can provide more specific analyses on a per-lease basis, and be used to test interactions among leases with respect to food depletion. This will be available at the end of the COEXIST project[1], i.e. April 2013.

Finding: The addition of mussels to the offshore aquaculture area does influence the performance of clam leases within the Ria Formosa, with respect to production. The scenario of full mussel production at the APPAA reduces food availability to the clam beds, with a projected 120 tonne annual decline in clam production. This would be equivalent to a first sale loss of about 1 200 000 €, which may be offset by commercialisation of mussels.

Recommendation: Stakeholder awareness of this trade-off is important. Model results should always be viewed as a support to decision-making, not an absolute truth. Despite this caveat, the ecological model is certainly sensitive to the introduction of a large cultivation area offshore of the Ria Formosa clam beds, and provides a first order assessment of impact. Further work integrating the finfish culture component should be carried out. This is beyond the scope of FORWARD, but will help understand (i) what the role of integrated multi-trophic aquaculture (IMTA) will be in mitigating food depletion for co-cultivated shellfish; (ii) to what extent particles emerging from fed aquaculture and fish waste may be relevant as a food source for clams within the Ria.

Finding: Both inshore clam culture and off-shore mussel culture can coexist from a production perspective.

Recommendation: A thorough assessment of the disease implications of the two culture areas and their interaction should be carried out. Work is ongoing in the COEXIST project on models to help inform this issue, and these may be integrated in the system-scale EcoWin2000 model if this research is successful. The relevance of potential disease threats both (i) within the separate inshore area (where *Perkinsus* seems to be already endemic) and within the offshore area (where close co-cultivation requires a clear, appropriate, and strictly enforced disease policy), and (ii) between the two areas, cannot be understated.

Finding: The EcoWin2000 model adequately simulates production, but the mortality component needs to be improved. This is largely due to inadequate data on mortality, added to the fact (as discussed above) that the timing and causes of mortality events are insufficiently understood. Models that use a broad spatial scale, and even models that use a more detailed grid, are unable to reproduce fine scale hypoxic events, likely to be the proximal cause of severe clam mortality.

Recommendation: A better understanding of mortality, using risk-based approaches as recommended above, can lead to tools that can be integrated with the E2K model (or others) to trigger mortality events and reproduce observed patterns. No model will be able to predict a clam mortality event e.g. one year

from now, because much hinges on water temperature, clam growth over a particular year, and other factors that are weather-dependent, or rely on social options, and are therefore unpredictable. However, any model that can mimic typical conditions, and test mitigation strategies, such as anticipation of harvest, will be of value both to managers and farmers.

Local-scale models

Finding: Simulation of clam production in intertidal areas is a practical way of assessing suitability. Local-scale simulations of pond culture may help in determining finfish culture density, and appropriate combinations of finfish and shellfish in integrated multi-trophic aquaculture (IMTA). The finfish pond culture model was validated using data kindly provided by the national fisheries institute, IPIMAR. For two replicate ponds, individual biomass after 134 days of culture was 303 ± 69 g (measured) and 277 g (simulated); after 246 days of cultivation the fish had an average biomass of 367 ± 51 g (measured) compared with 396 g (simulated).

Recommendation: The Farm Aquaculture Resource Management (FARM) model is available to the local water resource and fisheries managers and through them to the growers' associations for use by farmers. Both the onshore and inshore culture can be examined. The environmental drivers for both the shellfish and finfish models can be taken from existing data (see database section in the Tools chapter), or from simulations using the system-scale model.

The FORWARD book is organised in five main chapters. Each chapter is designed to be readable on its own, allowing a focus on particular aspects of the work that may be of greater interest. But the whole is unquestionably greater than the sum of the parts. A brief description of the chapters and content is given below.

Following a general overview, the reader is invited to learn about aquaculture in the Ria Formosa, and review the toolset developed and applied in FORWARD; the next chapter looks at sustainability, and includes natural, social, and governance components. It is here that the main results of models are presented. The final chapter is devoted to management analyses and recommendations. The book is completed with a series of four case studies, focusing on: (i) sediment dynamics, a key aspect of a barrier island system; (ii) the production and environmental effects of a 15 km² IMTA aquaculture park situated offshore of the Ria Formosa; (iii) diseases in aquaculture and lessons learnt from other parts of the world; (iv) the corporate side of the aquaculture business, with a focus on vertical integration.

THE FORWARD PROJECT

AQUACULTURE IN EUROPE AND THE WORLD

The work described in the FORWARD book addresses the prospects for sustainable development of aquaculture in the Ria Formosa, an area that has been used for wild shellfish harvest since the days of the occupation of the Iberian Peninsula by the Moors, more than thirteen hundred years ago, and for clam cultivation for over the last two centuries.

Data from the most recent FAO report on fisheries and aquaculture, published in 2010, define a milestone in the relationship between the two

activities: aquaculture, with an annual production of about sixty million tonnes, is now equal in volume to capture fisheries; furthermore, future trends are an increase in aquaculture and a stabilisation or reduction of wild fisheries.

The data projection in Figure 10 indicates that this point will have been reached in September 2011, taking into account the fraction of fish used for human consumption. Part of the wild catch (25-30%) is used for other purposes, including production of feed for aquaculture. In agriculture this critical point, i.e. where farming overtook hunter-gathering, was reached 10 000 years ago in the Neolithic Period.

FIGURE 10   Capture fisheries for human consumption and aquaculture

Capture fisheries for human consumption

September 2011

$r^2 = 0.99$, $p < 0.01$

Aquaculture

Live weight (10^6 tonnes per year)

Year

■ ■ Data points   .... Extrapolation

CARRYING CAPACITY AND THE ECOSYSTEM APPROACH

The concept of carrying capacity in aquaculture, based on four pillars of sustainability (Figure 2), has been adapted to include governance, considered more relevant than the physical element, which in many respects is encapsulated in the production component. Governance, on the other hand, is clearly missing from the original model and the quality of balanced regulation, stakeholder involvement, and community-based management often constitutes the difference between sustainable aquaculture and an environmental time bomb.

The bulk of the projected thirty million tonnes y^{-1} of additional aquatic products required to feed the planet by the year 2050, when the world population is expected to reach nine billion, will undoubtedly be cultivated in developing countries, principally in Asia, but also in South America, and potentially in Africa.

In Europe, annual growth of aquaculture has declined to 1%, partly because of market factors, but also because the industry is subject to stringent regulation and sustainable development is a major consideration. Recent environmental legislation, such as the European Union's Water Framework Directive (WFD; 2000/60/EC) and Marine Strategy Framework Directive (MSFD; 2008/56/EC) has implicitly promoted the three objectives of the Ecosystem Approach to Aquaculture (EAA), namely (i) human well-being; (ii) ecological well-being; and (iii) multi-sectoral integration.

THE POLIS PROGRAMME

The FORWARD (Framework for Ria Formosa water quality, aquaculture, and resource development) project is part of a set of plans developed by Polis Litoral Ria Formosa S.A. - Sociedade para a Requalificação e Valorização da Ria Formosa (polislitoralriaformosa.pt/), in particular its P6 plan: Plano de valorização e gestão sustentável das actividades ligadas aos recursos da Ria (Plan for sustainable management and value-added of activities associated to the resources of the Ria).

Another component of the P6 project was developed by the Portuguese Institute for Fisheries and Sea Research (IPIMAR), focusing on environmental quality and sustainability of the biological resources of the Ria Formosa.

THE RIA FORMOSA

The Ria Formosa (36º 95' 87'' to 37º 17' 53''N and 8º 04' 97'' to 7º 51' 69'' W) is a dynamic and complex coastal system, located in the Algarve province of southern Portugal (Figure 11).

The Ria is 55 km long, located in the leeward coast of the Algarve, and occupies an area of 184 km^2. Two peninsulas (Cacela and Ancão) and five islands (Culatra, Barreta, Armona, Tavira e Cabanas) form the land boundaries, which enclose a shallow lagoon system. These islands are separated by different tidal inlets which form a dendritic channel system. The volume of the Ria varies between 45-210 X 10^6 m^3, the tidal range between 0.9-3.0 m. Water temperature oscillates between 16-29ºC and salinity is about 36 psu.

The Ria Formosa is simultaneously a natural reserve, Portugal's most productive aquaculture area, and the focus for a number of other economic activities, all of which must be reconciled in order to coexist harmoniously.

The watershed draining to the Ria Formosa has an area of about 745 km^2 and has a high spatial complexity; it is divided into two main regions, mountains and loamy plains ('barrocal'). The mountains have a more humid climate, poor soils, and relatively impermeable bedrock; it

FIGURE 11 The Ria Formosa and associated watershed

Altitude (m)
500
250
0

0 2.5 5 10 15 20 kms

Watershed Aquifers Urban areas / Coastal system: Ria Formosa Atlantic coast
WWTP. Discharge area: Ria Formosa Stream network
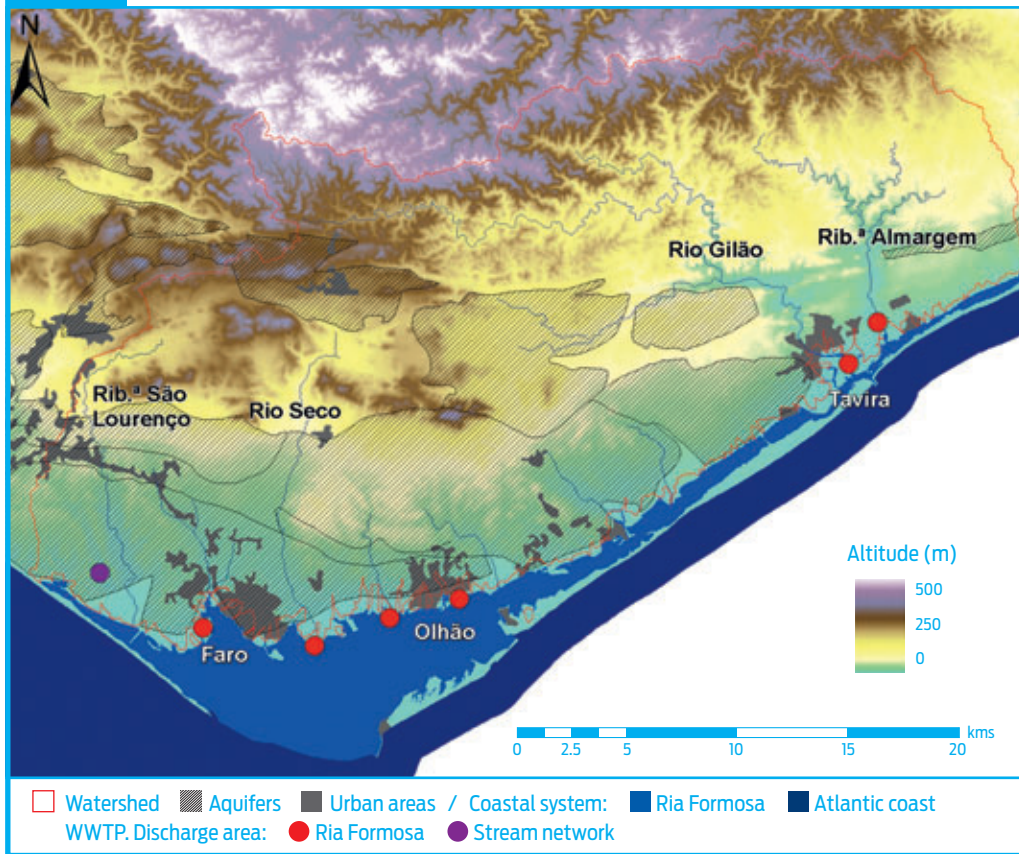
is covered by Mediterranean shrubland and less intensive agriculture, and is drained by the two main rivers: Rio Gilão and Ribeira de Almargem. The 'barrocal' has a drier climate, with more fertile soils and highly permeable bedrock with several aquifers; this allows the co-existence of rainfed orchards with intensive orchards and vegetable gardens which are irrigated with groundwater.

The region is drained by small streams with a torrential regime. The cities of Faro, Olhão, and Tavira are the main economic and touristic centers, interacting with the Ria also through wastewater discharges from Waste Water Treatment Plants (WWTP).

WATER RESOURCES AND AQUACULTURE IN PORTUGAL

The public water domain comprises the public maritime domain, the public domain of lakes and rivers, and the public domain of remaining waters. The public maritime domain belongs to the state.

The private use of public domain water resources for the practice of aquaculture is subject to a prior license, with a maximum term of 10 years. However, if an investment cannot be amortised within this period of time, a concession contract with a maximum duration of 75 years may be considered.

SCOPE AND OBJECTIVES OF THE STUDY

The FORWARD project began in January 2010, had a duration of two years, and a spatial extent encompassing the whole of the Ria Formosa (Figure 11).

FORWARD combined fieldwork, laboratory experiments, and mathematical models. Models were developed for the watershed loads to the Ria, including the effects of agriculture and effluents, exchanges with the ocean, sediment interactions, and growth and production of clams and other species.

TABLE 2	Outputs of the FORWARD project		
Type of output	**Details**	**Objectives**	**Product**
Experimental and field data	Fine scale measurements on the clam beds	Better understanding of food availability	Report and FORWARD book
	Culture practice for aquaculture	Essential for correct simulations of cultivation at both system and local scales	Spreadsheets (see Aquaculture chapter)
Databases	Relational databases with historical data and water quality data collected by IPIMAR	Consolidate and make available data to end users, exploit for model calibration and validation	BarcaWin2000 relational databases (historical and FORWARD project)
Models			
Geographical Information Systems (GIS)	GIS layers for water quality, uses, policy, and legislation	Select appropriate areas for cultivation, i.e. apply principle 3 (multisectorial balance) of EAA	ArcGIS layers and bespoke website at http://goodclam.org/gis
Catchment	Model for the drainage basin	Allow managers to explore different land use and effluent discharge scenarios, particularly for compliance with EU directives	Fully calibrated and validated Soil and Water Assessment Tool (SWAT), and training. Suitable for managers
Hydrodynamics and water circulation	Model for the extended domain, including the offshore Armona IMTA area	Support integrated management of the coastal zone, analyse hydrodynamic connectivity e.g. from a disease standpoint	Calibrated and validated Delft3D model, training. Suitable for specialist technical staff
Shellfish and fish growth	Models for Good Clam, Manila clam, Pacific oyster, Mediterranean mussel, and gilthead bream	Provide tools for easy assessment of individual growth. Rapid scoping of growth and environmental effects. Suitable for farmers and managers.	WinShell and WinFish models, simulating individual growth and environmental effects for shellfish and finfish
System-scale aquaculture	Model for extended domain, incorporating cultivated species, land discharges, water circulation, and spatial uses	Assess system production, environmental effects, and ecological carrying capacity. Analyse scenarios	Calibrated and validated EcoWin2000 ecological model, training. Suitable for managers
Farm-scale aquaculture	Model for open water shellfish culture in intertidal areas, or IMTA in offshore leases at Armona	Assess production, environmental effects, and economics at the lease scale	FARM model for cultivated fish and shellfish. Suitable for farmers and managers
	Model for onshore monoculture and IMTA	Assess production, environmental effects, and economics at the pond scale	FARM model for cultivated fish and shellfish. Suitable for farmers and managers

Marine spatial planning of a range of activities, including salt production and wildlife reserves was also modelled with GIS. These activities were supported by direct measurements, *in situ* trials at cultivation sites, and complementary data.

The tools supplied by FORWARD are used to analyse and optimize carrying capacity of the Ria Formosa, both at the local scale and for the system as a whole. The FORWARD products support decision-making on sustainable carrying capacity for the different areas of the Ria, in order to reduce the mortality of cultivated animals and harmonise aquaculture with other uses of the system. Furthermore, these products may be used by growers and their associations to optimise culture practice in order to maximise profits.

The main outcomes of FORWARD are:

Better understanding of the processes that drive aquaculture in the Ria Formosa, both onshore and in the water body;

Integration of marine spatial planning, dynamic models at system and local scales, and social aspects;

Analysis of the opportunities and limitations to management resulting from natural, social, and governance elements;

Definition of a framework for improving sustainability of natural resource use, taking into account projected interactions between offshore culture and traditional inshore clam and oyster cultivation.

The two chapters that follow in this book describe aquaculture in the Ria Formosa, and review the toolset developed and applied in this project; the following chapter looks at sustainability, and includes natural, social, and governance components. It is here that the main results of models are presented. The final chapter is devoted to management analyses and recommendations. The book is completed with a series of four case studies, focusing on: (i) sediment dynamics, a key aspect of a barrier island system; (ii) the production and environmental effects of a 15 km^2 IMTA area situated offshore of the Ria Formosa; (iii) diseases in aquaculture and lessons learnt from other parts of the world; (iv) the corporate side of the aquaculture business, with a focus on vertical integration.

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AQUACULTURE IN THE RIA FORMOSA

SOCIO-ECONOMIC CHARACTERISATION

The resources of the lagoon system are an important source of revenue for a large part of the population of the Ria Formosa area. One of the most important activities is shellfish and finfish aquaculture. Aquaculture plays a very important role in production, which is reflected in the number of active leases. The vast majority of producers cultivate shellfish. In 2001 there were 1245 leases, of which 1224 were for bivalves. In 2010 there were 1122, i.e. the pattern remained unchanged.

There is also a parallel unlicensed activity of bivalve collection. This involves an unquantified number of inhabitants, and an unknown volume, but it may provide a living for the unemployed, and those at risk of social exclusion—hence it has a potential social value. However, it is unregulated and may affect the competitiveness of legally authorised aquaculture.

FIGURE 12   Uses of the Ria Formosa

- Finfish aquaculture. Number of finfish aquacultures = 19, Number of leases = 14
- Farms. Total area = 480 ha, Number of plots = 1302, Number of leases = 1122
- Offshore aquaculture area (APPAA)
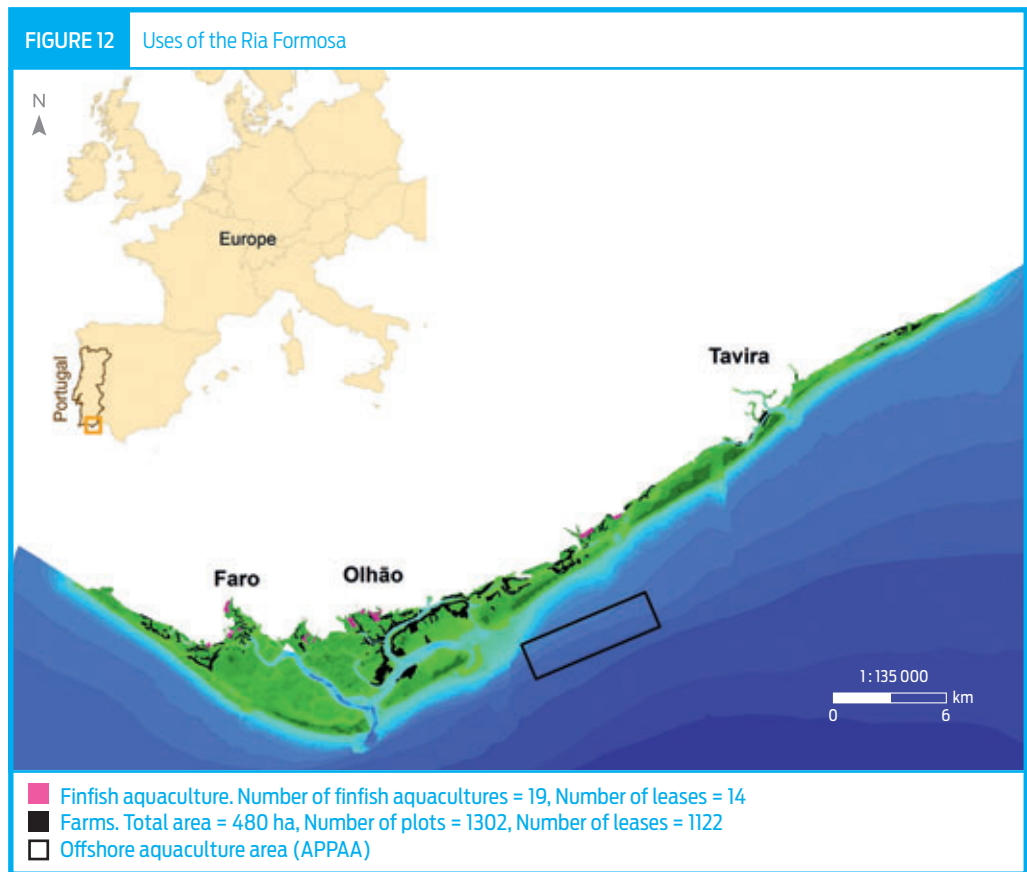
Aquaculture licencing

In Portugal, aquaculture practice requires a permit for use of the water resources and a license for the activity. The permit-issuing authority is the Administration of the local Hydrographic Region, and the license for the activity is granted by the Directorate-General for Fisheries and Aquaculture.

In order to simplify procedures and make life easier for growers, a 'one stop desk' was created, where farmers now have a single contact point to deal with the whole licensing process.

Production

Aquaculture in the Ria Formosa represents 41% of the Portuguese national production (Table 3), and is mainly composed of bivalve shellfish, with a small finfish production.

Shellfish aquaculture in Ria Formosa is one of the most significant local economic activities with respect to renewable resources. Major species are the Good Clam (2100 t y^{-1}) and the oyster (183 t y^{-1}), both farmed in the intertidal zone of the Ria (Figure 12). The reported production is sourced from official statistics, but much higher values are often mentioned: ~ 5000 t y^{-1} for Good Clam and ~ 2000 t y^{-1} for the oyster.

Finfish culture takes place mainly in onshore ponds (Figure 12). The main farmed species are seabream (*Sparus aurata*), sea bass (*Dicentrarchus labrax*) and meagre (*Argyrosomus regius*). The Pilot Area of Aquaculture Production of Armona (APPAA, Figure 12), located in the offshore area opposite the inlet of Olhão, has a total area of 1440 ha divided into 60 leases for finfish (70%) and bivalve (30%) production.

Bivalve culture practice

Different species of bivalves (clams, cockles, and oysters) can be grown in mixed culture at shellfish lease sites (Figure 12), although cultivation mostly consists of clam monoculture, with a small area used for oyster monoculture.

Good Clam culture

Table 3 illustrates the uncertainty that exists in terms of production and value of the Good Clam aquaculture activity.

TABLE 3	Declared production of fish and bivalves in the Ria Formosa in 2010		
Species	Production (tonnes)	Value (1000 €)	Farmgate price (€ kg^{-1})
Good Clam (*Ruditapes decussatus*)	2100	19 851	9.5
Oyster (*Crassostrea gigas/angulata*)	183	329	1.8
Cockle (*Cerastoderma edule*)	221	135	0.6
Total bivalves	*2504*	*20 315*	
Gilthead bream (*Sparus aurata*)	178	820	4.6
Sea bass (*Dicentrarchus labrax*)	170	1099	6.5
Meagre (*Argyrosomus regius*)	9	43	4.8
Total finfish	357	1963	
Total aquaculture	*2861*	*23 430*	

TABLE 4	Culture practice for the Good Clam (*R. decussatus*)	
	Seed	**Harvest**
Culture area		460 ha
Habitat	Natural recruitment banks in the Ria Formosa	Intertidal sediments, fine and medium sand, 10-12 cm depth
Habitat modification		
Seed origin	Natural recruitment	Addition of pebbles and sand
Density (ind. m^{-2})	300-1500 or 1 kg m^{-2}	100-150 or ~1-2 kg m^{-2}
Size (mm)	10-20	30-35
Total fresh weight (g)	1.5-2.5	6-13
Dry flesh weight (g)	0.003-0.09	0.3-0.4
Mortality (% ind.)	30-50	
Culture cycle (year)		2
Harvesting period		All year (+ summer and Christmas)
Harvest (months)		18-24
Reproduction (months)		March-Oct (1° year of life)
Spawning (months)	April-October	
Production (tonnes y^{-1})		2000-5000
First sale (€ kg^{-1})	3-5	10-13
Turnover (million €)		20-65
Population involved		10 000

The water quality of the Ria Formosa is classified as B, which requires shellfish depuration before marketing and consumption. The Good Clam production (Table 4) depends on the availability of seed (juveniles). Seeds from wild recruitment are collected by licensed operators in natural banks (Figure 13) for personal use or resale.

The leases are mostly small (Figure 36) and are modified by the producers by adding sand collected in the Ria Formosa and/or pebble (~0.5 cm in diameter). Producers use rakes, or motor ploughs to remove algae (e.g. *Ulva*) and seagrasses (*Zostera* spp.) and to level the ground. Juvenile clams are grown
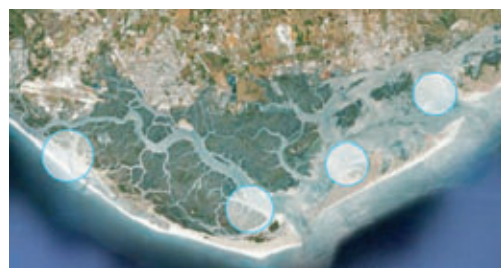
Figure 13. Natural banks for seed collection in the Ria Formosa.

together with adults, with no separation of year classes. The harvester uses a clam knife and separates juvenile clams from market-sized adults.

Figure 14. Harvester's knife for clams.

Oyster culture

The natural recruitment of the Portuguese oyster (*Crassostrea angulata*) is not sufficient for aquaculture and this species is normally intended for the producers own consumption.

Seed of the Pacific oyster (*Crassostrea gigas*) comes from abroad (e.g. France) and is introduced in the Ria Formosa. Oysters are initially grown on trestles and subsequently transferred to the bottom (Table 5).

PROBLEMS ASSOCIATED WITH AQUACULTURE

Problems with culture practice

Some of the current culture practices of in the Ria Formosa are not in accordance with the regulations of the Ria Formosa Natural Park (Table 6).

Non-indigenous species

There are several potential problems associated with the introduction of non-indigenous species, including the adaptation and spread of new species that compete with native species, hybridization between native and introduced species, the transport of pathogens and diseases through transportation/relocation of seeds and clams, and cross-contamination between different types of shellfish. One of the major concerns for growing Good Clam is the introduction of foreign Manila clam seed. Large quantities of Manila clam seed were introduced in the Ria Formosa in the late 1980s and between 2002-2004, and a further 635 t in 2006. The two species are easily distinguished but the native species is considered of better quality and has far greater market value.

The *Perkinsus* parasite can be transported by the clam seed. The introduction of Pacific

TABLE 5	Culture practice for oysters (*C. gigas* and *C. angulata*)	
	Seed	Harvest
Culture area		Unknown (~8 ha?)
Habitat	Natural lower intertidal zone	Natural lower intertidal zone
Habitat modification		Bags 20 cm above the bed (trestles), transferred to sediments
Seed origin	Nursery and natural recruitment (France)	
Density (ind. m^{-2})	1000-1200 or 350-600 / bag	400 or ~200 / bag
Size (mm)	5-20	40-80
Total fresh weight (g)	0.8-1.1	35-50
Dry flesh weight (g)	0.01-0.03	0.7-1.1
Mortality (% ind.)	5-10	30-40
Culture cycle (year)		1
Harvesting period		All year (+ summer and Christmas)
Harvest (months)		10-15
Reproduction (months)		Feb-Oct (1° year of life)
Spawning (months)	April-October	
Production (tonnes y^{-1})		2000
First sale (€)	0.013 - 0.02 (per individual)	3 (per kg)
Turnover (€)		7 000 000
Population involved		~100?

TABLE 6	Culture practices that violate the regulations of the Ria Formosa Natural Park
Practice	Observation
Debris and other deposits	Use of gravel and debris in the Ria Formosa Natural Park
Application of sand	Addition of sand to level the culture plot and avoid formation of tide pools at low tide. This practice raises the sediment level above the mean low water. mark The compaction of sediment areas is also prohibited
Application of pebbles	Addition of pebbles to culture plots to reduce erosion and predation
Plot delimitation	Use of extraneous materials such as bricks, PVC pipes, or tiles to enclose areas for cultivation
Fencing	Addition of materials to protect the plots adjacent to navigation channels from erosion
Mechanisation	Use of mechanized equipment is prohibited unless specifically authorized
Unlicensed collection	Unlicensed collection of seed, causing a negative impact on the local economy. Recreational catch (with or without license) is also a concern for producers, with tons of clams being removed annually from the Ria Formosa

Figure 15. Gill disease (dermo - white nodules) caused by *Perkinsus*.

oysters may also have brought some parasites to the Ria Formosa, e.g. the copepod *M. ostreae*. At present, natural recruitment of oysters is contains both the Portuguese oyster *C. angulata* and the Pacific oyster *C. gigas*, as well as hybrids of the two species, which makes the certification of the Portuguese species unfeasible.

Mortality of the Good Clam

The mortality rate of Good Clam can be very high (up to 80-90%) during the summer months. This mortality apparently results from physiological stress due to infection by

the protozoan parasite *Perkinsus atlanticus*, and to a reduction of energy reserves post-spawning, along with environmental cofactors in unfavorable conditions: temperatures between 15-20ºC, lower dissolved oxygen concentration, salinities higher than 18 psu and substrate degradation. The parasite causes gill lesions (Figure 15) that decrease the respiration rate.

Discharges from Waste Water Treatment Plants (WWTP), erosion from navigation, and sedimentation resulting from a lack of water circulation due to the modification of the bathymetry of the Ria Formosa, are of great concern to the producers.

The perception of the growers is that the mortality of farmed animals and the reduction of the production in recent decades are on the one hand associated with the nutrient and microbial discharges from WWTP, and on the other from the inadequate water flow due to silting.

Nevertheless (Figure 16), the evolution of the bacteriological status of the production area of Olhão between 1990 and 2009 indicates an increasing percentage of areas are classified as Class A, i.e., where the animals may be consumed without prior depuration.

FIGURE 16 Microbiological status of the production area of Olhão between 1990 and 2009

Class: A B C
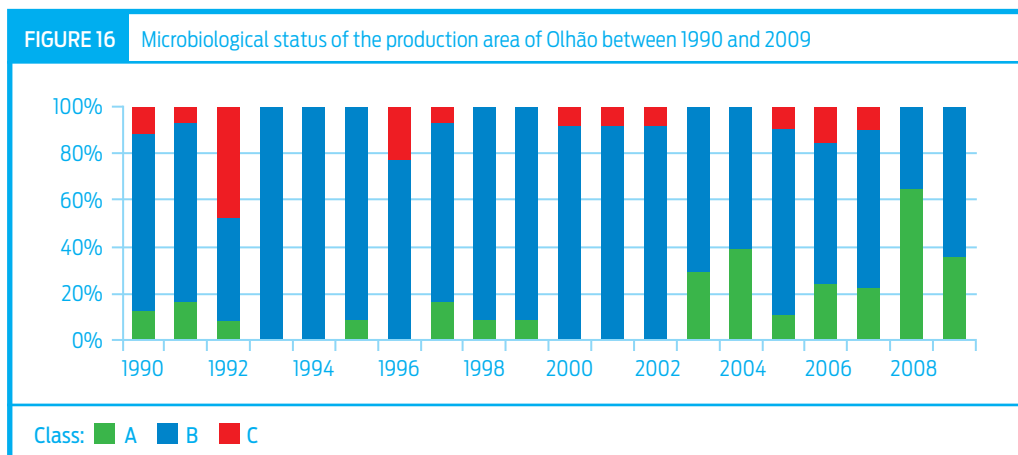
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TOOLS

The following chapter reviews the tools that were developed and used in the FORWARD project (Figure 17).
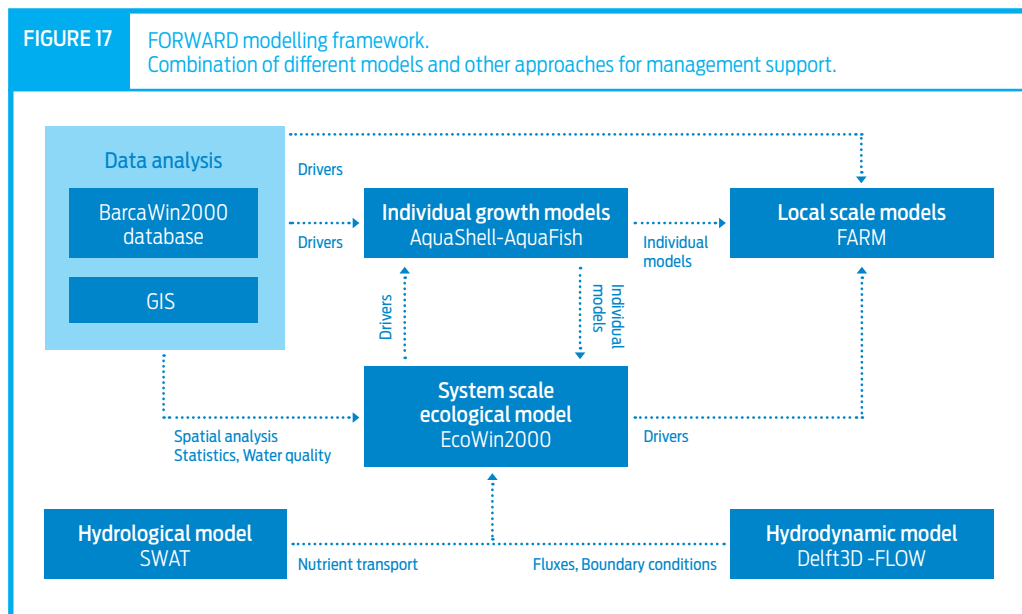
SUPPORTING TOOLS

Database

This relational database was built with Barcawin2000 (B2K). It holds water quality data collected by IPIMAR, as well as historical data obtained over the last decade in European and national research projects (about 10 years of data, with 97 000 records). The software allows the user to retrieve individual temporal or spatial data sets and export these to Excel spreadsheets for post-processing.

The B2K database was used in FORWARD to set initial conditions of the EcoWin2000

(E2K) ecological model, to perform calibration and validation, and to extract data to run the local models.

Fieldwork and Laboratory

Small scale experiments (Figure 19) were conducted for a better understanding of the Ria Formosa system, in order to reduce the uncertainty. The experiments outputs were incorporated into mathematical models. Relations between carrying capacity elements including hydrodynamics, food supply, and animal behaviour were measured with specialized instruments. Physiological (filtration rate, morphological relationships), physical (velocity, turbulence, re-suspension), and biological (food quality and quantity above the bed) measurements were made for several tide cycles over for different types of substrate.

FIGURE 17 FORWARD modelling framework.
Combination of different models and other approaches for management support.
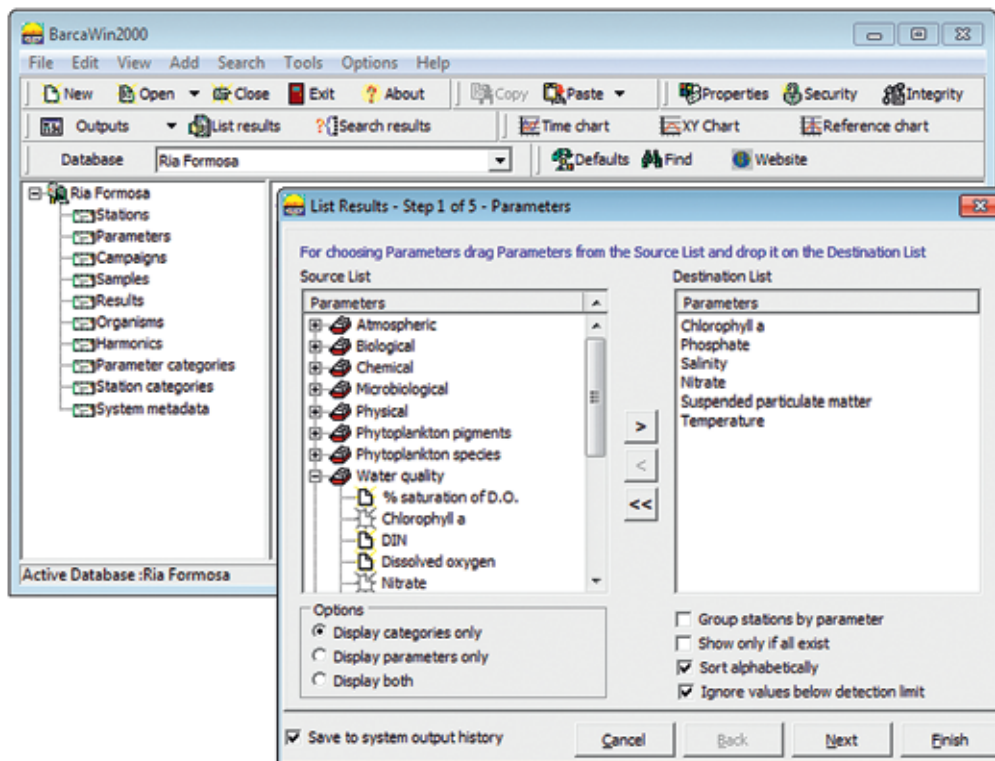
Figure 18. BarcaWin2000 database for FORWARD project.

Geographic Information Systems

The Geographic Information Systems (GIS) were used as the basis for the integration of the spatial information of the system. All data were georeferenced in the of Gauss-Kruger Lisbon Datum projection.

GIS was used for:

| Spatial visualisation of data;

| Identification of activities, spatial planning support and generation of bathymetry

| Calculation of areas and definition of box boundaries for the E2K model.

MANAGEMENT TOOLS

Models

The modeling tools used in the FORWARD project were: SWAT watershed loading model, fine-scale hydrodynamic model, individual growth models (AquaShell for shellfish, AquaFish for fish), EcoWin2000 system-scale ecological model, and the FARM local scale model for inshore, coastal and offshore aquaculture.

SWAT

The SWAT (Soil and Water Assessment Tool) model analyses human impacts on watersheds. The model simulates processes related
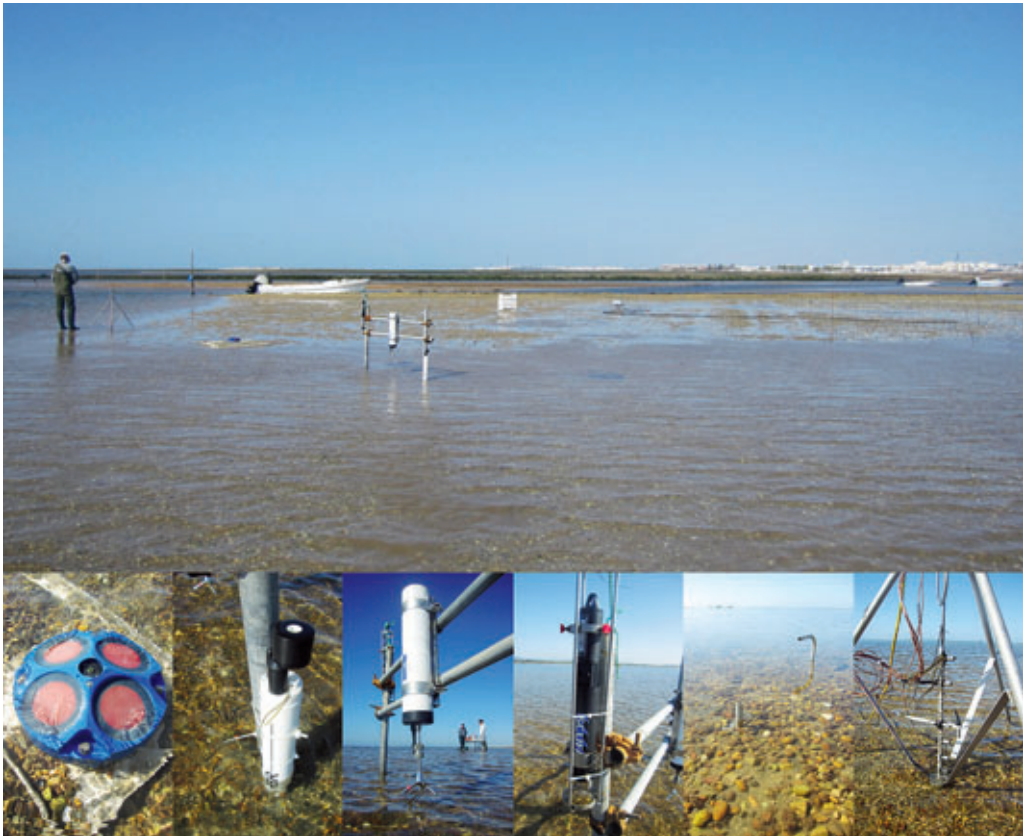
Figure 19. Site for small scale experiments. Highlight of the instruments used.

TABLE 7	Main GIS layers produced during the FORWARD project	
Data	Map type	Data model
Bathymetry	Image (raster)	Grid
Activities	Vectorial	Polygons and lines
Model boxes	Vectorial	Polygons
Coastline	Vectorial	Polygons and lines
Water bodies (WFD)	Vectorial	Lines
Monitoring stations	Vectorial	Points

to vegetation growth, hydrology, soil erosion, nutrient and pesticide transport, agricultural soil use and waste water treatment plant (WWTP) discharges (Figure 20).

SWAT may also simulate different types of land-use management, water resources management and climate scenarios.

| TABLE 8	Summary of tools used in FORWARD	
Name	Description	Expertise required
Barcawin2000 (B2K)	Relational database software. Contains data on water quality	Minimum expertise. Easy to use
Fieldwork and laboratory	Physiological, physical and biological measurements over several tidal cycles and different substrates.	Advanced user. Large team and specialized material
Geographic Information Systems (GIS)	GIS layers for water quality, usage, policy and legislation	Advanced user
Soil and Water Assessment Tool (SWAT)	Analyses the human impacts in river basins. Scenarios for the management of land use, water resources and climate scenarios	Advanced user. Specific data needed.
Delft3D-FLOW	Three-dimensional hydrodynamic model. Simulations of currents, sediment transport, waves, water quality, morphology and ecology of the system.	Advanced user. Specific data needed.
AquaShell, AquaFish	Individual growth models for shellfish and fish, with environmental effects on species.	Minimum expertise
FARM	Evaluation of aquaculture, environmental effects and economics at local scale	Minimum expertise
EcoWin2000 (E2K)	Evaluation of system production, environmental effects and ecological carrying capacity. Analysis of scenarios.	Advanced user

FIGURE 20 Ecohydrological modelling stages
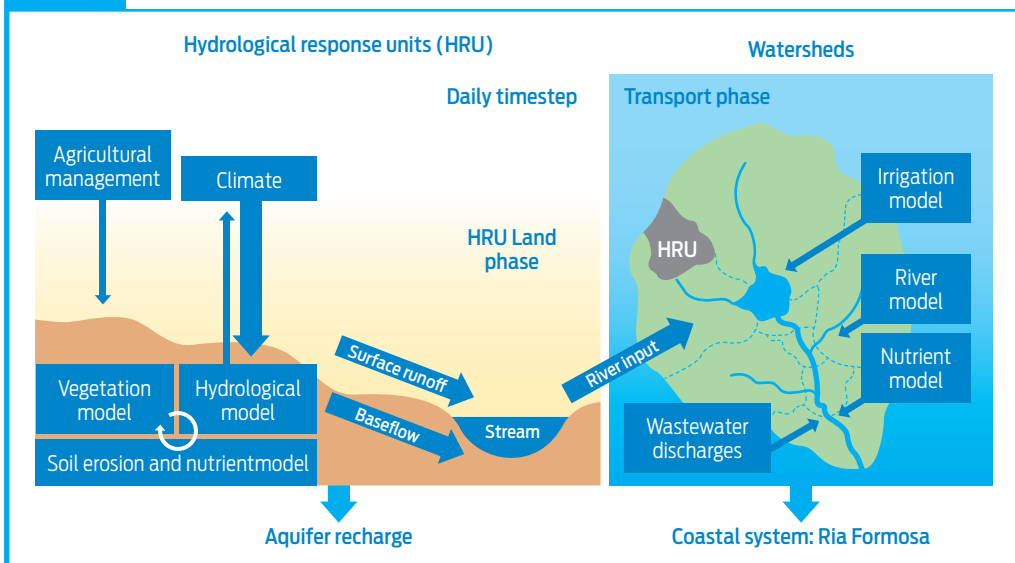
Delft3D-FLOW

Delft3D is an industry-standard, open source, 3-dimensional hydrodynamic model, that simulates water circulation and transport of suspended and dissolved substances forced by atmospheric (e.g. wind, heat exchange) and hydrological factors (e.g. tides, density differences). The computational grid has a resolution of 30 m in the narrows (e.g. Farol inlet, Figure 21) and in areas of large bathymetry gradients, 100 m inside the lagoon and 500 m offshore, with 33 000 calculation points and 7 vertical layers. The model domain spans 80 km in the east-west direction and 12 km south of the Farol inlet.

Individual growth models

AquaShell

The individual growth model for the Good Clam was developed from the generic AquaShell model for bivalves. This model uses an energy balance approach, and functions that represent bivalve physiology. The model incorporates the main physical and biogeochemical components, allometry, and provides results on the bivalve production and environmental impacts, both in the water column and sediment.

AquaFish

The AquaFish individual growth model is based on net energy balance, and uses a similar rationale (i.e. maximum simplicity) to the AquaShell model developed for bivalves. By contrast to organically extractive shellfish aquaculture, finfish are fed (dry feed pellets in the West but often trash fish in SE Asia)—one of the key indicators of finfish aquaculture is the feed conversion ratio, or FCR, so the feed supplied must be accounted for in the model. Another key difference in simulating feeding is that a concentration-based approach, as is normally used in shellfish models, is not appropriate, since gilthead (and other fish species such as salmon and bass) eat a 'meal'; this is best thought of by considering that in the wild,
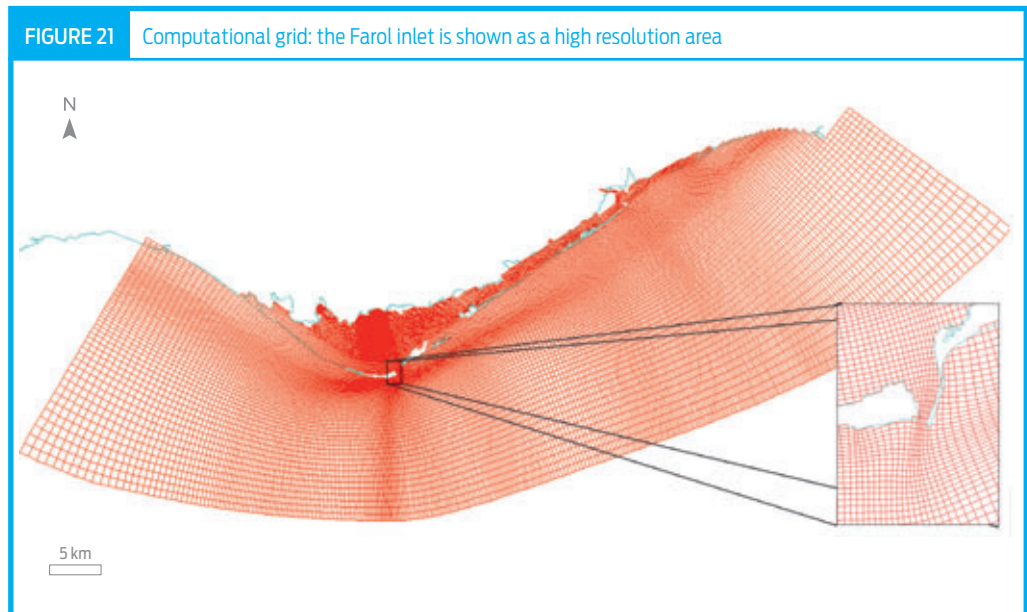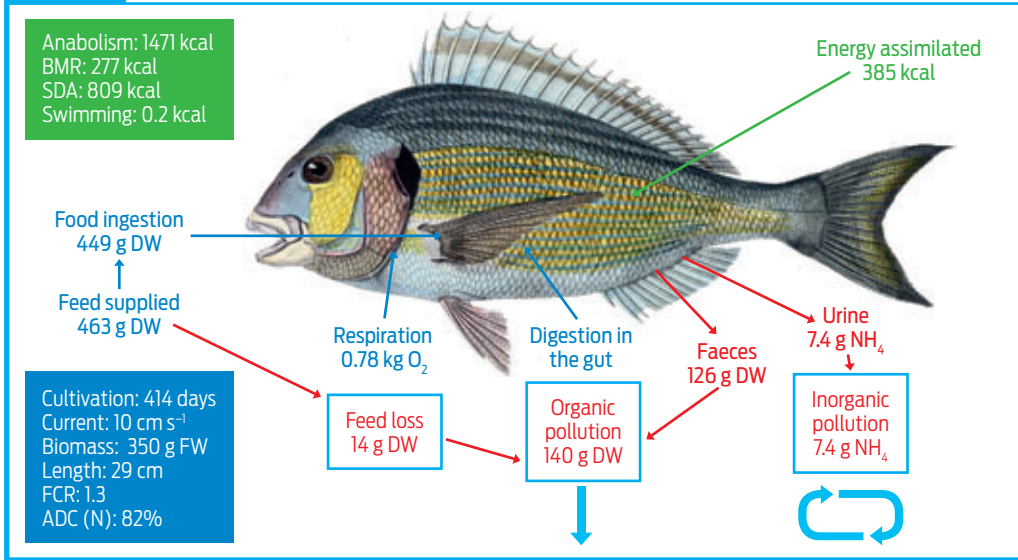

FIGURE 21 Computational grid: the Farol inlet is shown as a high resolution area

N

5 km

FIGURE 22 AquaFish individual model for gilthead seabream

Anabolism: 1471 kcal
BMR: 277 kcal
SDA: 809 kcal
Swimming: 0.2 kcal

Energy assimilated
385 kcal

Food ingestion
449 g DW

Feed supplied
463 g DW

Respiration
0.78 kg O_2

Digestion in
the gut

Faeces
126 g DW

Urine
7.4 g NH_4

Cultivation: 414 days
Current: 10 cm s^{-1}
Biomass: 350 g FW
Length: 29 cm
FCR: 1.3
ADC (N): 82%

Feed loss
14 g DW

Organic
pollution
140 g DW

Inorganic
pollution
7.4 g NH_4

gilthead thrive on a diet of discrete prey items such as mussels, crustaceans, and smaller fish. Figure 22 illustrates the types of outputs that can be obtained with the model.

EcoWin2000

EcoWin2000 (E2K) is an ecological model for aquatic systems, based on object oriented programming. E2K resolves the hydrodynamics and biogeochemistry, and can also include an analysis of the population dynamics of selected species.

EcoWin2000 is composed of two main parts: i) the central core—the module responsible for communication between among objects, the user interface, production of model results, and routine maintenance tasks, and ii) the 'ecological' objects. Each object includes a number of state variables or forcing functions, and the object-oriented architecture makes it easy to derive new objects tailor-made to a specific ecosystem. EcoWin2000 has been used for studies of pollution, eutrophication,
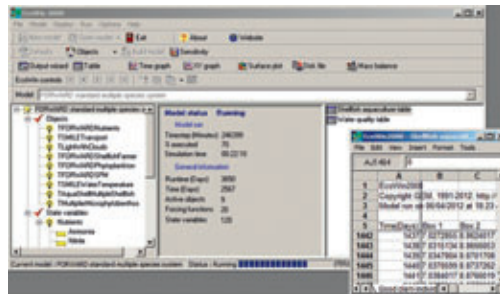
Figure 23. EcoWin2000 (E2K) model run for system-scale simulation of the Ria Formosa ecosystem.

and aquaculture sustainability. It has been applied in many parts of the world, and is a potential tool to support the ecosystem approach to aquaculture (EAA), as recommended by FAO.

In the FORWARD project, E2K was used to implement the system-scale ecological model for the Ria Formosa and adjacent shelf, in order to estimate production and to simulate management scenarios.

FIGURE 24 FARM layout for IMTA—integrated multi-trophic aquaculture

Farm length

Width

Current

Current

Finfish and/or shellfish

Chl *a*

Chl *a*

Depth

POM

POM

1   2   3   n-1   n

Sections

POM

POM

FIGURE 25 Web-based management system with GIS layers
for uses, field data, and model results for the Ria Formosa.

Cacela

Tavira

Faro

☐ Clam leases   ☐ Coastline   ■ Offshore aquaculture lease   ■ Offshore aquaculture area
■ Cacela artificial reef   ■ Tavira artificial reef   ■ Olhao artificial reef   ■ Faro artificial reef
■ Natural park   ☐ EcoWin2000 offshore boxes

FARM

The FARM (Farm Aquaculture Resource Management) model (Figure 24) simulates aquaculture at the local scale for offshore, coastal, or o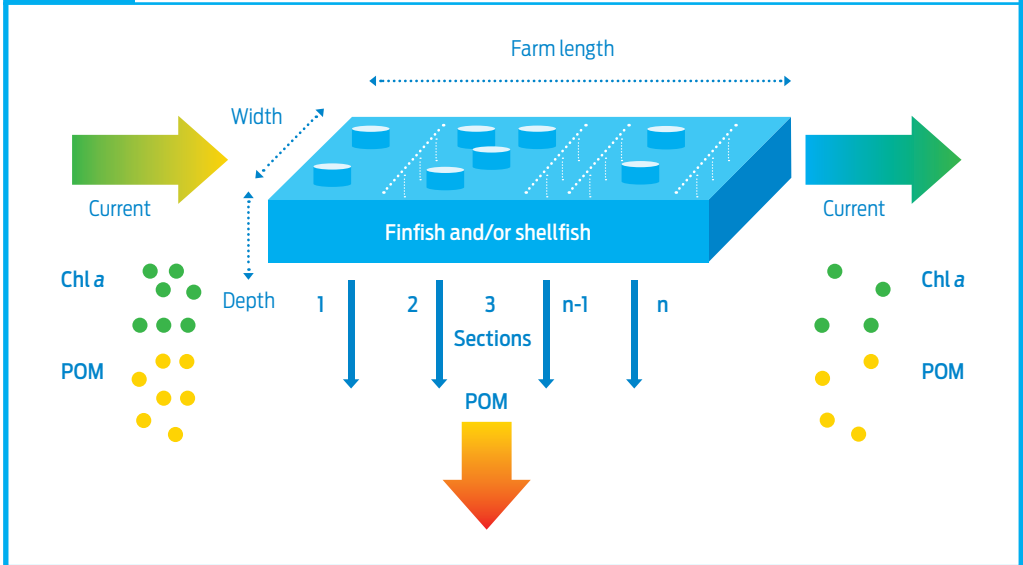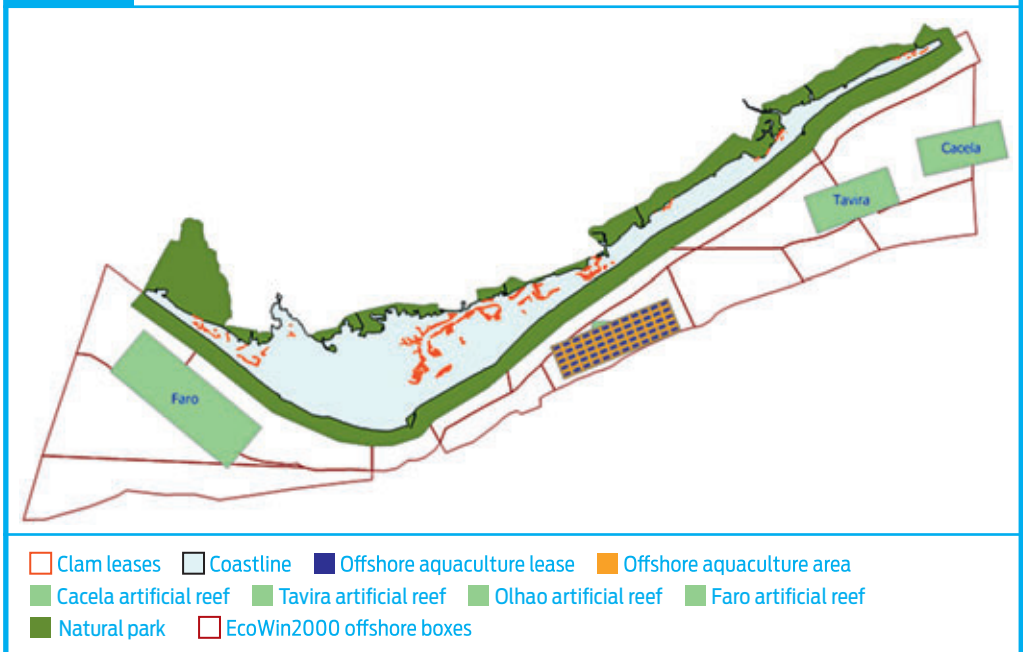nshore sites. The model can be applied to fish and / or shellfish, and combines physical and biogeochemical models, shellfish and fish growth models, and cost-benefit models. Environmental effects are calculated both at the level of sediments and in terms of eutrophication in the water column. This type of model is targeted at both the producer and manager.

Geographic Information Systems

In the FORWARD project, the goodclam.org/gis website illustrates how a range of different layers can be combined to provide results to the public and allow managers to drill down into specific aspects of the Ria Formosa, including measured data, uses, and modelling results.

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SYSTEM SUSTAINABILITY

The FAO Ecosystem Approach to Aquaculture (EAA) establishes that sustainable aquaculture should satisfy the following conditions:

| Ecological balance;

| Social equity;

| Harmonisation of multiple uses.

The analysis of aquaculture sustainability carried out in FORWARD, and developed below, is based on this framework.

ECOLOGICAL BALANCE

The models applied in FORWARD (see Tools chapter) were implemented to simulate the conditions under which aquaculture presently occurs.

The final analysis depends on the linkage of the various models, but the results of the separate components (including field experiments) are of great value.

FIGURE 26 Time series of current speed over a clam bed for a tidal cycle, at a height of 2-20 cm above the sediment.
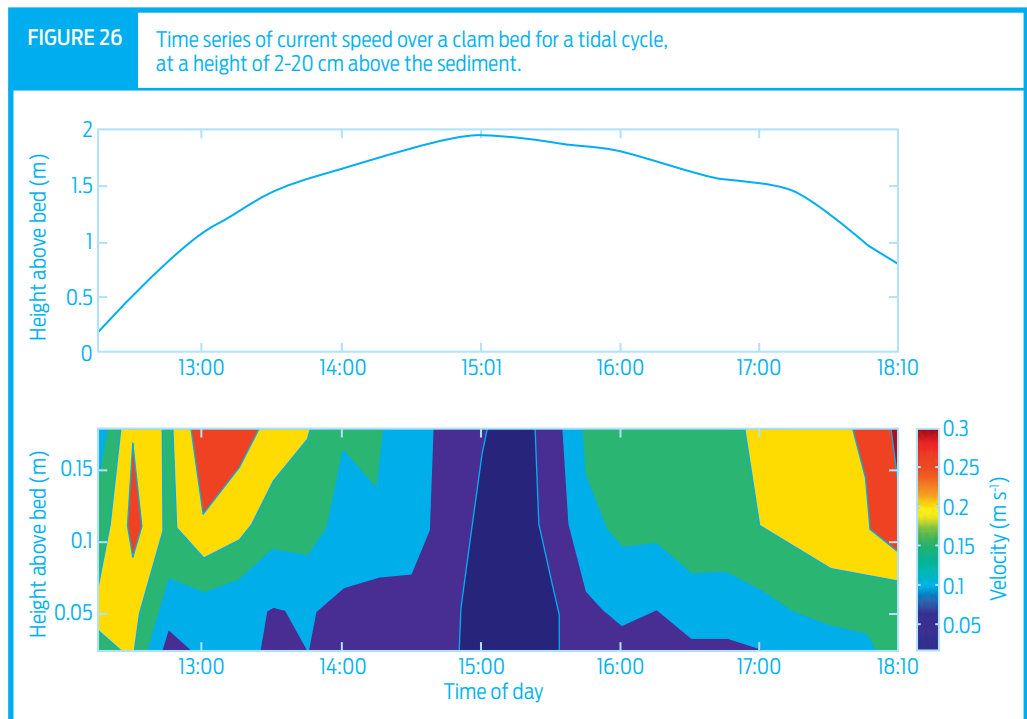
Field experiments

These experiments were carried out by deploying instrumentation close to the clam beds at Fortaleza, to study the small-scale hydrodynamics, and the amount and type of food available to clams and oysters.

The maximum recorded velocity in the water column above the clam bed was 0.34 m s^{-1} The results provided information about the speed vector in intertidal areas (Figure 26); the flood tide flows northwards and a reverse flow occurs during the ebb.

Filtration rates of 1.23 L g^{1} (DW) h^{1} for Good Clam and 2.7 - 3.8 L ind^{-1} h^{-1} for cockles were measured. The morphometric measurements made during the fieldwork were used to calibrate the individual growth models.

The Good Clam feeds on phytoplankton, microphytobenthos (in the sediment) and detritus. During the flood tide, sea water rich in algae enters the Ria and flows over the culture areas. Consequently, at the high tide there is a chlorophyll peak (Figure 27) followed by lower concentrations during the ebb.

The vertical profile of chlorophyll over a clam bed shows food depletion near the bed (Figure 27). Re-suspension of algae close to the bed seems to occur at or near the turn of the 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}. If we consider the existence of microphytobenthos to a depth of 2 mm of the bed and a sediment density of 2600 kg m^{-3}, the microphytobenthos concentration would be 20-40 mg m^{-2}, an order
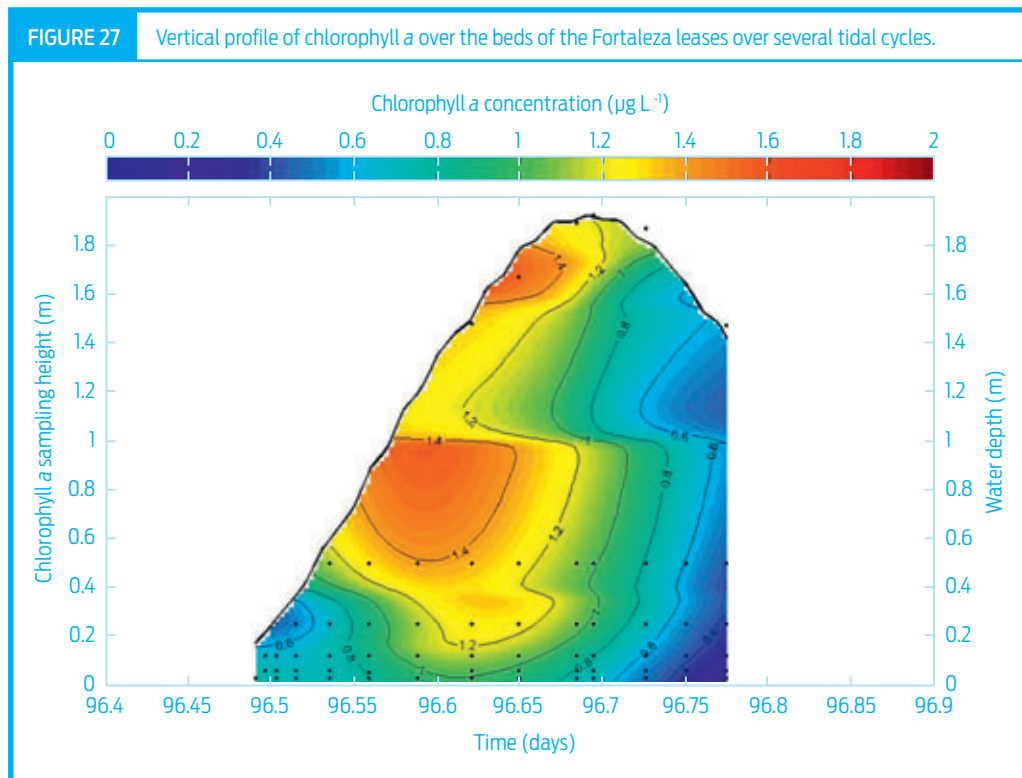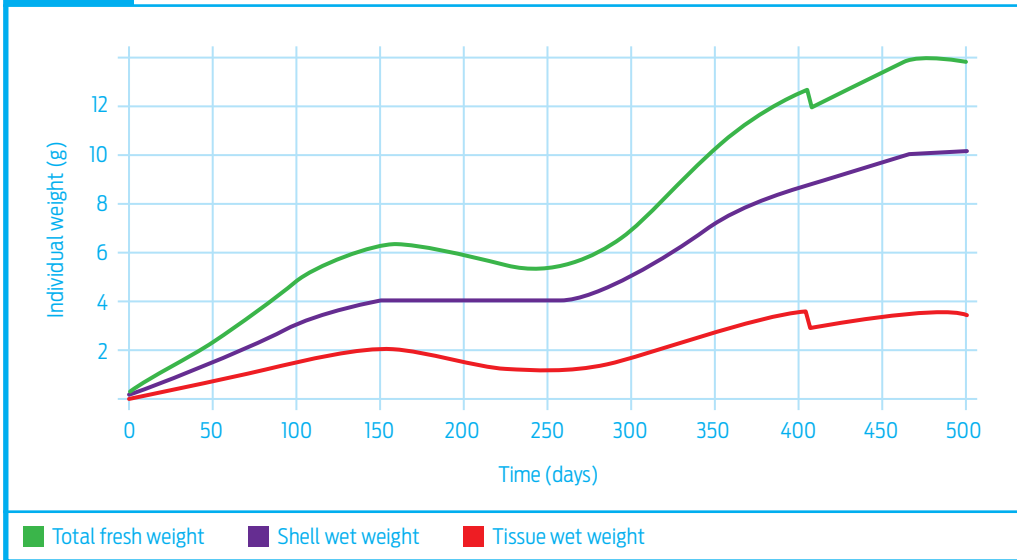

FIGURE 27 Vertical profile of chlorophyll *a* over the beds of the Fortaleza leases over several tidal cycles.

FIGURE 28 Individual growth of Good Clam (*Ruditapes decussatus*).

Legend: Total fresh weight | Shell wet weight | Tissue wet weight

of magnitude higher than the concentration of phytoplankton (1-2 mg m⁻²). In addition, not all the phytoplankton is accessible to the clams and oysters.

It seems reasonable to assume that microphytobenthos is an important food source for the cultivated bivalves, and that this may explain the preparation of plots for clam cultivation - according the farmers, a clam bed has to change color ('cook') prior to seeding, otherwise the animals will not survive. This may also explain anecdotal evidence that small (3 cm) oysters are moved from the trestles to the sediment when they begin to produce 'dirt', i.e. to release more faeces and pseudofaeces.

Individual bivalve growth

The AquaShell model was used to simulate individual growth of both Good Clam and oyster. A microphytobenthos food component was added to the model.

The model was calibrated for Good Clam based on literature data, sampling campaigns and experiments conducted in the area of Fortaleza - Olhão during the FORWARD project (October 2010 and April 2011) . The simulation results for clam biomass are presented in Figure 28.

This model simulates the growth and environmental impacts, both in the water column and sediment. The individual model was incorporated into both the system scale ecological model and the local scale model, in order to simulate the production at the population scale, i.e. focusing on the marketable cohort.

Reference period for modelling

The reference period was established for the hydrological year 2007/2008 (October to September) after cross-referencing existing data. On the one hand, the meteorological dataset required to force the watershed and hydrodynamic circulation models has the

required data between 2001 and 2008. On the other, the wastewater treatment systems in Faro, Olhão and Tavira were reconfigured between 2006 and 2007, and therefore the modelling period should be subsequent to that. The rainfall in 2007/2008 was close to the average between 1981 and 2009, so this can be considered a representative year in terms of climate. Models based on a hydrological year allow the simulation of the system's behavior in the wet (autumn and winter) and dry (spring and summer) seasons.

Hydrology

Modelling of watershed loads

The Ria Formosa watershed is a source of nutrients and other pollutants, mostly derived from urban point-source loads, and diffuse loads coming mostly from agricultural areas. Point-source loads are concentrated in WWTP located mostly around major urban areas (Figure 11), and are relatively constant in time. Diffuse loads are transported either via the surface stream network, entering the Ria through the various stream outlets, or via subsurface flows, through percolation to the aquifers and subsequent transport to the Ria, entering the system in a spatially-distributed way through the bottom sediment layer. They are concentrated in the wet season (October to March), mainly during high rainfall periods.

Three methods were used to estimate these loads: (i) direct quantification of WWTP loads, (ii) modelling diffuse loads from the stream network, and (iii) estimating aquifer loads from measurements in the Ria Formosa sediments.

The estimation of WWTP point-source loads considered the main plants (project population over 3000 inhabitants, or 1% the total

project population in the study area) discharging to the Ria Formosa or the watershed, operational during the hydrological year 2007/08. 7 WWTP in 20 were analyzed, containing 99% of the project population (shown in Figure 11); Six of these have direct discharges to the Ria Formosa and one discharges to a stream inside the watershed. Estimates were based on monthly effluent analyses, supplied by ARH Algarve, which include several parameters such as water flow, suspended solids, phosphorus and nitrogen. It should be noted that the Faro Noroeste WWTP was replaced after the simulation period; the new WWTP led to an important decrease in per capita discharges, which means that the results of this estimate are probably above present-day loads.

The simulation of diffuse loads was made using the SWAT – Soil and Water Assessment Tool ecohydrological model. It was selected for its capacity to simulate the main hydrological processes in the Ria Formosa watershed in their surface and subsurface (unsaturated soil and shallow aquifer) components. The model uses a daily timestep for a multi-annual period; it is able to evaluate each surface water body as defined in the Water Framework Directive and its sub-catchments. It is especially suited to simulate water, solids, nitrogen and phosphorus loads.

The SWAT application was based on the collection of an extensive data base, including cartography (digital elevation model, stream network, soil map, lithology map, land-use map), meteorology (SNIRH and GLOBALSOD networks), hydrometry (SNIRH network) and water quality (SNIRH network and Univ. Algarve measurements). These data were pre-analysed to exclude dubious measurements, estimate missing values, and calculate relevant parameters.

FIGURE 29 Comparison between simulations and observations in Rio Gilão for daily streamflow (2007/2008; SNIRH measurements for the Bodega hydrometric station).

Legend: Rainfall ▪ Observed streamflow ▪ Simulated streamflow
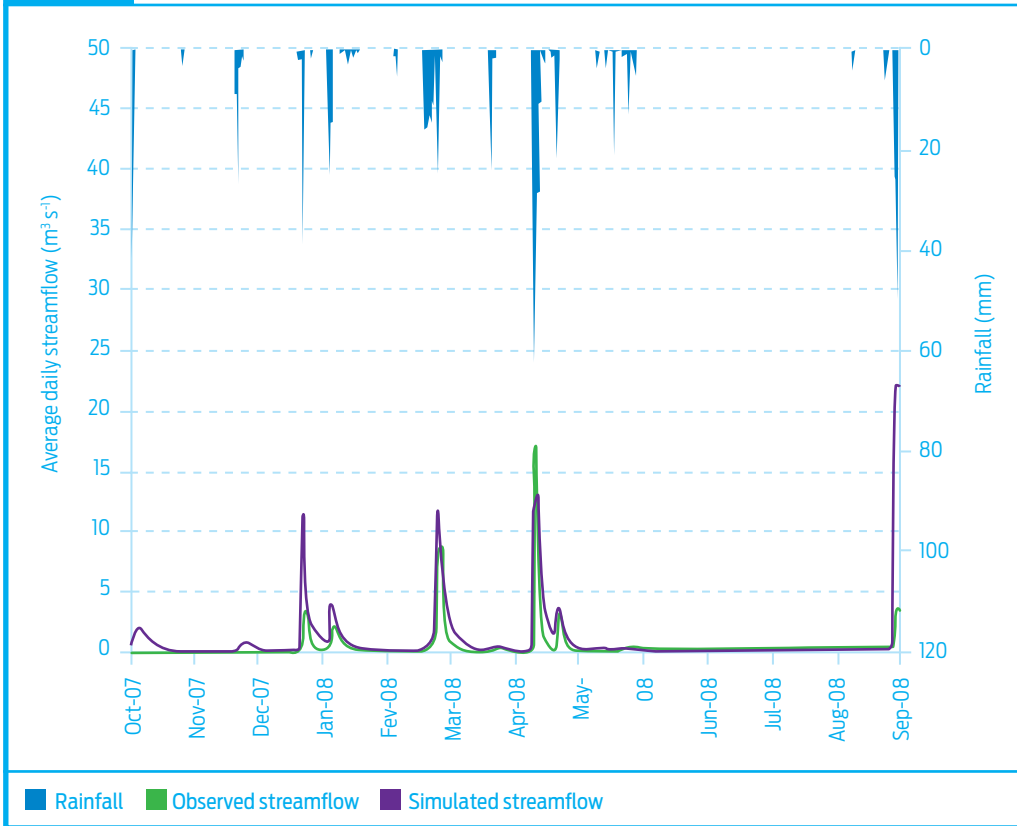
The model was applied from October 2001 to September 2008, with four stabilization years beforehand. All sub-basins larger than 400 ha inside the Ria Formosa were considered; this value resulted from a compromise between simulating the largest possible area and minimizing model complexity. Only the part of the watershed upstream from the Ria Formosa transition zone was considered, therefore excluding salt pans, coastal salt marshes and part of the main urban areas. The resulting simulated area consists of 19 catchments draining to the Ria Formosa, with a simulation area of 637 km^2. These were divided into 50 sub-basins, with a median area of 9.4 km^2, which tried to consider the water bodies defined for the Water Framework Directive as well as transition points between different bedrock types, the main WWTP discharge points, and the location of hydrometric and water quality measurement stations.

This area is divided into Hydrological Response Units (HRUs): regions with the same combination of land use, soil type and slope, inside a given sub-basin; SWAT provides individual results for water balance and nutrients for each HRU. Land-use and soil type classes were aggregated to simplify the simulation, maintaining nonetheless model representativity of the study area. HRUs with less than 100 ha were integrated in the nearest HRU.

FIGURE 30 NO$_3$ exports in peak and low flows, 2005/2006.

■ Observed nutrients ■ Simulated nutrients
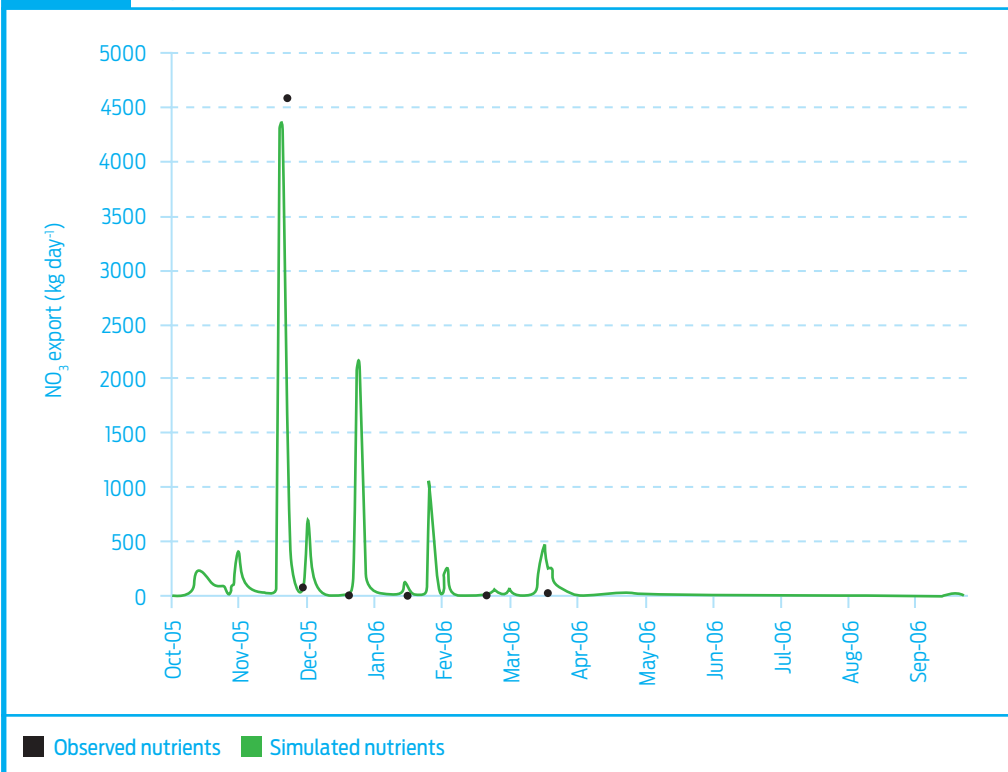
As a result, the Ria Formosa watershed was sub-divided into 331 HRUs. These were parameterized for dominant cultures/vegetation types, agricultural practices (including fertilization and irrigation), soil properties, and hydrogeology, based on previous applications of SWAT for Mediterranean catchments.

Model results were evaluated for 11 hydrometric stations in the SNIRH network, and 10 water quality measurement points, including the SNIRH network and some peak flow nutrient measurement points. Calibration focused on reproducing both annual water and nutrient exports, and peak water and nutrient flows for days of heavy rainfall, in an effort to create a representative parameterization for the entire watershed (including ungauged streams) and

avoid an over-calibration with the existing hydrometric data.

The results show an adequate simulation of streamflow and nutrient exports (Figure 29 and Figure 30), although the model evaluation for nitrogen and phosphorus is limited by the low sampling frequency, which only allows for an evaluation of the order of magnitude of exports during peak flow periods.

The lack of data on nutrient exports to aquifers has limited the evaluation of SWAT model results for these processes. However, it can be said that the simulated results (Figure 31) are at the correct order of magnitude; the export estimates of 600 ton N/year agree with published values of 700 ton N/year, and the

FIGURE 31 Estimated nutrient loads to the Ria Formosa from land, for the hydrological year 2007/2008.
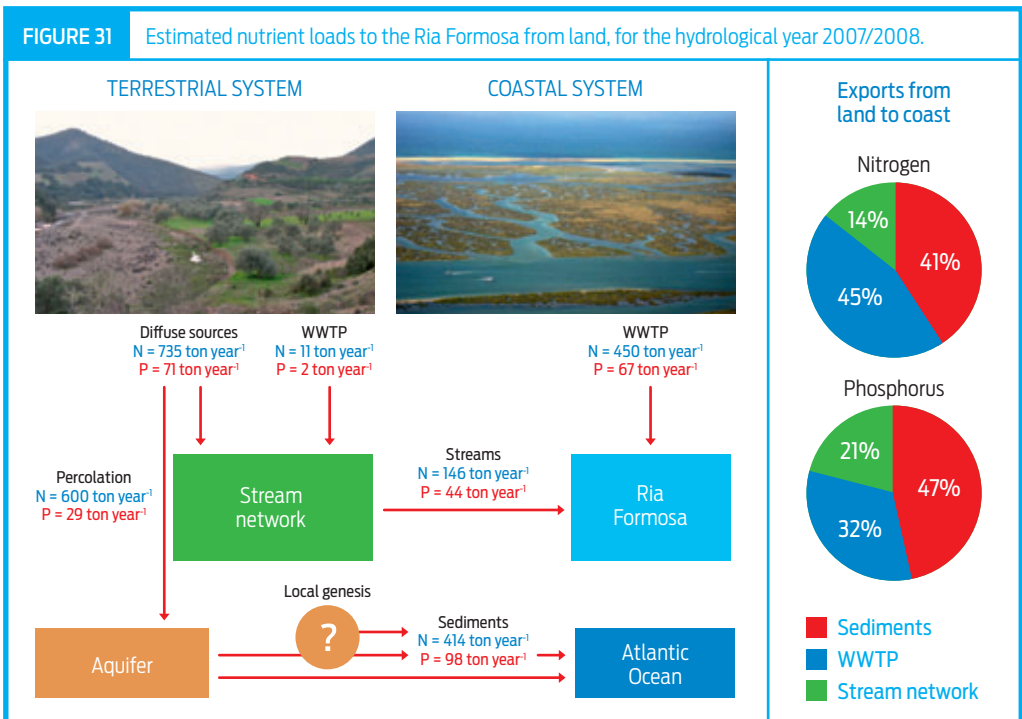
simulated NO^3 concentration in the percolated flow is similar to that measured in the aquifers: ~10 mg N L^{-1}.

Due to the uncertainties associated with nutrient flows from the aquifer to the Ria Formosa, the estimate of aquifer loads was based on nitrogen and phosphorus export measurements in the sediments. They incorporate aquifer loads but also other sources, such as organic matter decomposition and diagenesis.

The combined results from the watershed loads estimate, resulting from the evaluation of WWTP discharges, SWAT model application, and analysis of nutrient loads from sediments, are shown in Table 9. Nutrient sources and transport processes through the stream network and aquifers are illustrated in Figure 31.

The uncertainty associated with aquifer-sediment transfers should be noted, due to issues related to both the temporal scale (nutrients percolated to aquifers might take several years

TABLE 9	Estimated nutrient loads to the Ria Formosa during the hydrological year 2007/2008.	
Source	**N (ton/year)**	**P (ton/year)**
WWTP (direct discharge)	450 (45%)	67 (32%)
Stream network	146 (14%)	44 (21%)
Sediments	414 (41%)	98 (47%)
Total	1010	209

Sediments   Stream network   WWTP   Rainfall

to reach the Ria Formosa) and the interaction with other factors, namely nutrient genesis in the sediments from processes such as organic matter decomposition and diagenesis.

Overall, WWTP and sediments are the main nutrient sources to the Ria Formosa, while the stream network has loads with a smaller but still significant importance.

However, the importance of nutrient sources changes when daily loads are analyzed (Figure 32). While daily WWTP and sediment loads are relatively constant (0.7 to 1.8 ton nitrogen, and 0.1 to 0.6 ton phosphorus), stream network loads are concentrated in periods with high rainfall and streamflow; they are usually negligible, but daily loads of 27 ton nitrogen and 15 ton phosphorus are attained during the

TABLE 10	Estimated nutrient loads to the Ria Formosa between 8 and 12 April, 2008.	
Source	N (ton)	P (ton)
WWTP (direct discharge)	7 (12%)	1 (4%)
Stream network	43 (78%)	19 (90%)
Sediments	5 (10%)	1 (5%)
Total	55	21

TABLE 11	Estimated nutrient loads (tonnes) to the Ria Formosa per geographic region.							
		Western		Central		Eastern		
Period	Source	N	P	N	P	N	P	
Annual	WWTP (direct discharge)	398	57	9	~0	43	6	
	Stream network	34	12	20	9	92	22	
8-12 April 2008	WWTP (direct discharge)	6	1	~0	~0	1	~0	
	Stream network	5	3	11	6	27	10	

maximum flow period (8 to 12 April 2008). During this period, terrestrial streamflow loads are dominant (Table 10).

In spatial terms, there is a difference in the concentration of loads along the Ria Formosa. Table 11 shows the nutrient loads to the Ria Formosa per region: western (until Olhão), central (between Olhão and Tavira) and eastern (from Tavira onwards).

The streams and WWTP in these regions are shown in Figure 11; sediment loads are assumed constant. It can be observed that, in annual terms, the western Ria is dominated by WWTP loads, while the central and eastern regions are dominated by stream network loads, although the WWTP loads are still important. During the peak flow period, loads in the western Ria are equally divided between WWTP and the stream network, while the central and eastern regions show negligible WWTP loads.

Nitrogen and phosphorus loads calculated with SWAT were used as terrestrial inputs for the EcoWin2000 ecological model. Since these loads are simulated based on land-use and other factors, SWAT allows managers to analyze changes to agricultural patterns, urban discharges, and other watershed management issues (Table 12).

Circulation

Hydrodynamic modeling

The Ria Formosa is a shallow tidal lagoon, connected to the continental shelf by multiple inlets, with a convoluted structure of tidal channels. These morphological characteristics lead to a complex hydrodynamic response, mainly to the semi-diurnal, mesotidal forcing, responsible for an exchange of 50 to 75 % of the total volume over each tidal cycle.

TABLE 12	SWAT model application – main conclusions.
Finding	Detail
In 2007/08, WWTP were important nutrient sources for the Ria Formosa, but only contribute a part of the total loads	45% nitrogen, 32% phosphorus
Important sediment loads with uncertain origin; a part possibly comes from contaminated aquifers	41% nitrogen, 47% phosphorus
The annual importance of diffuse sources is difficult to estimate; streamflow contributions are smaller but important, aquifer contributions are unknown	Streams: 14% nitrogen, 21% phosphorus
Dominant streamflow contributions during peak flow periods	78% nitrogen, 90% phosphorus from 8 to 12 April 2008

TABLE 13	Dates of bathymetric surveys.

Area	Year
Entire domain	1979-80
Faro channel	2000
Secondary channels	2001
Tavira inlet	2001
Fuzeta inlet	2002

FIGURE 33 Hydrodynamic model: Salinity under intense precipitation conditions. a) horizontal distribution at Fuzeta; b) horizontal distribution at Tavira; c) vertical distribution at Tavira (section marked in black in b).
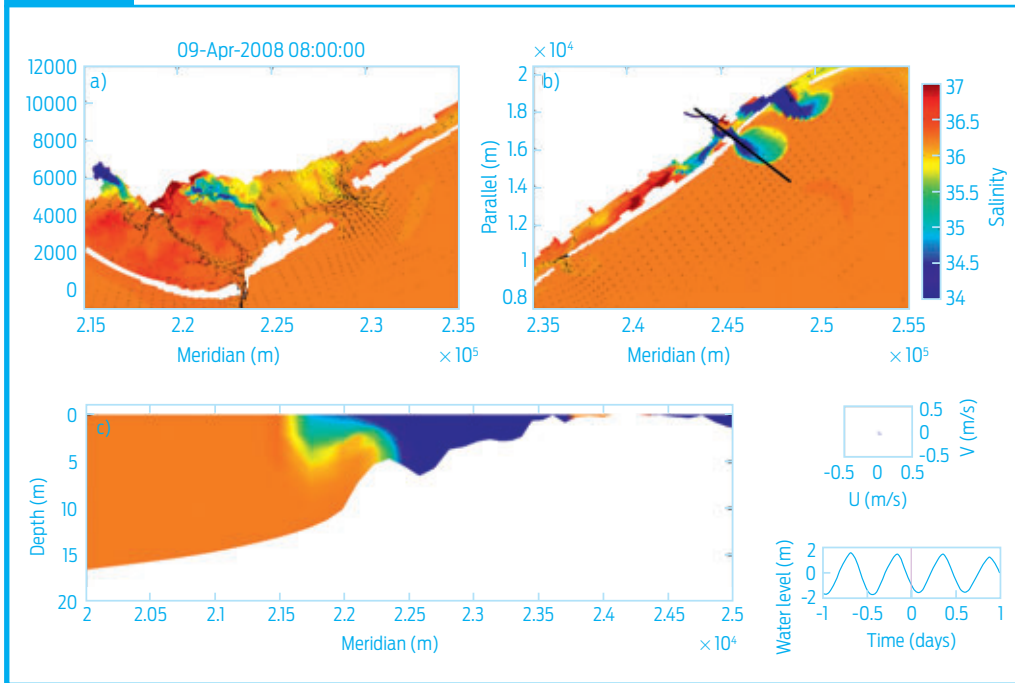
Hence, the key elements to model inside the Ria and its inlets were the system's semi-diurnal and fortnightly tidal cycles, together with the residual circulation generated by the interaction between the tide and bathymetry.

Heat and water exchanges with the atmosphere have a very small role in regulating the temperature and salinity inside the lagoon but, together with momentum fluxes, are of paramount importance in the simulation of offshore temperature in the vicinity of the Ria. Due to the large fraction of the water volume exchanged every tidal cycle, it was necessary to model an area including all of the Ria Formosa and the adjacent continental shelf up to the 30 m isobath (Table 13)
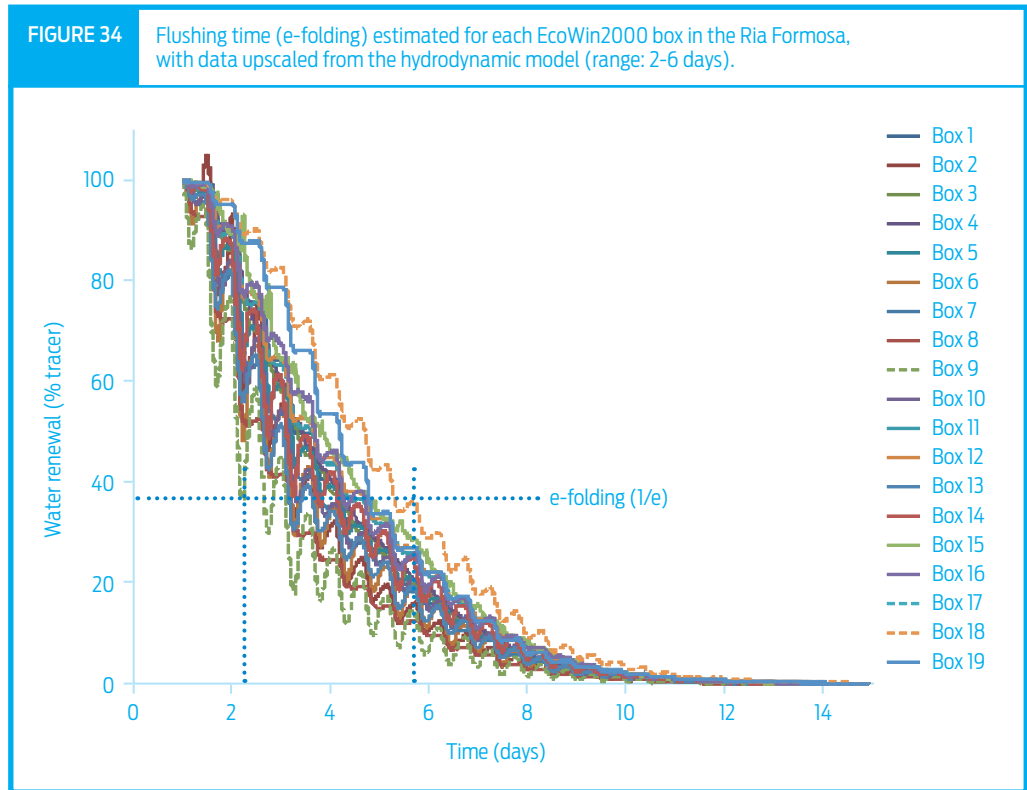
The tide was forced at the boundary using the FES2004 global tide model and was calibrated

by adjusting the Manning bottom roughness in depth classes for the 1979-1980 bathymetric survey and comparing the results against lagoon-wide water level surveys for the same period. These roughness depth classes were then applied to the 2001 bathymetric data and the results verified against a new dataset. The model was found to adequately represent the tide at the shelf, inside the lagoon and at the Ancão, Farol and Tavira inlets (Figure 33). At the remaining inlets, their fast morphodynamic response leads to an inadequate solution of the model at these sites.

To allow the simulation of the temperature and salinity fields at the offshore aquaculture site and to simulate the exchange between the lagoon and shelf under different near-offshore density field conditions, the model was forced at the boundaries by a time-varying profile extracted from a mesoscale ROMS (Regional Ocean Modelling System) model. The heat exchange between the atmosphere and ocean was simulated using a set of atmospheric parameters from the Faro Airport and NCEP reanalysis. Freshwater input was taken from the SWAT catchment model.

High freshwater runoff and east winds were found to transport water over the inner continental shelf from the eastern cell of the lagoon to the region of influence of the western cell. In east wind conditions, complete mixing of the water column was found as far as the 20 m isobath, creating the conditions for a higher fraction of re-incorporation of previously flushed lagoon water and consequently longer flushing times.

FIGURE 34 Flushing time (e-folding) estimated for each EcoWin2000 box in the Ria Formosa, with data upscaled from the hydrodynamic model (range: 2-6 days).
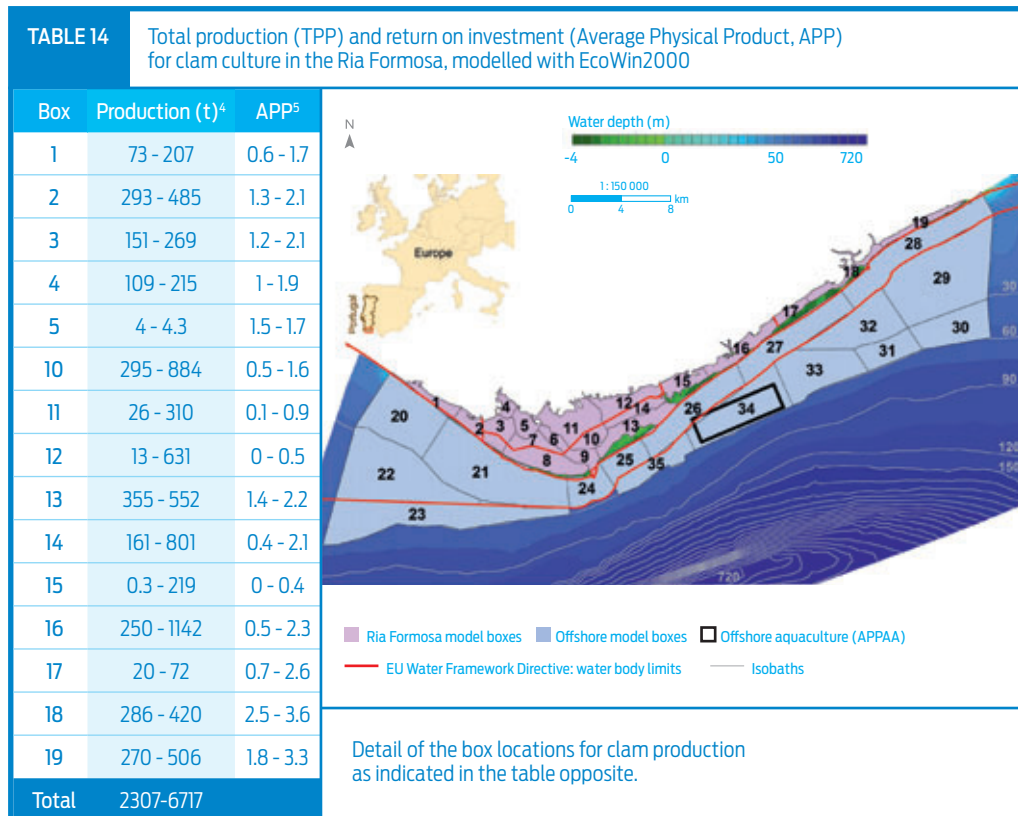
Upscaling

Due to the bathymetric complexity of the Ria and continental shelf and the need to resolve the vertical dimension in several layers, the hydrodynamic model needs to partition the space into about 100 000 calculation cells, with a resolution of 100 m; this limits the calculation timestep to a maximum of 30 seconds. These scales make no sense for ecological modelling, given that the simulated properties are approximately uniform at the scale of a hectare, and that the tidal cycle can be well resolved with hourly time steps. The ecosystem model also contains a much larger amount of state variables, and a typical run will simulate a decadal period.

Consequently, in the ecological model the fluxes from the hydrodynamic model were upscaled to represent the exchange between E2K model boxes at space and time scales relevant to the ecology. The annual mass balance of water was preserved both at the box and system levels. The flushing (e-folding) times obtained with the ecological model vary between 2 and 6 days in different zones of the Ria Formosa (Figure 34).

System-scale carrying capacity

The combination of models for land discharge, circulation, and shellfish growth, was used in the overall framework of the EcoWin2000 ecological model.

Box	Production (t)[4]	APP[5]
1	73 - 207	0.6 - 1.7
2	293 - 485	1.3 - 2.1
3	151 - 269	1.2 - 2.1
4	109 - 215	1 - 1.9
5	4 - 4.3	1.5 - 1.7
10	295 - 884	0.5 - 1.6
11	26 - 310	0.1 - 0.9
12	13 - 631	0 - 0.5
13	355 - 552	1.4 - 2.2
14	161 - 801	0.4 - 2.1
15	0.3 - 219	0 - 0.4
16	250 - 1142	0.5 - 2.3
17	20 - 72	0.7 - 2.6
18	286 - 420	2.5 - 3.6
19	270 - 506	1.8 - 3.3
Total	2307-6717	

TABLE 14 Total production (TPP) and return on investment (Average Physical Product, APP) for clam culture in the Ria Formosa, modelled with EcoWin2000

Ria Formosa model boxes ▪ Offshore model boxes □ Offshore aquaculture (APPAA)
— EU Water Framework Directive: water body limits — Isobaths

Detail of the box locations for clam production as indicated in the table opposite.

On the basis of the current model calibration, the annual clam harvest in the Ria is estimated to be two thousand three hundred tonnes, which is above the values estimated from landings data by the fisheries agencies. These results consider only the food available in the water column, i.e. phytoplankton algae and organic detritus. The Average Physical Product, i.e. the weight ratio of harvest: seed, is an indicator of the productivity of different areas.
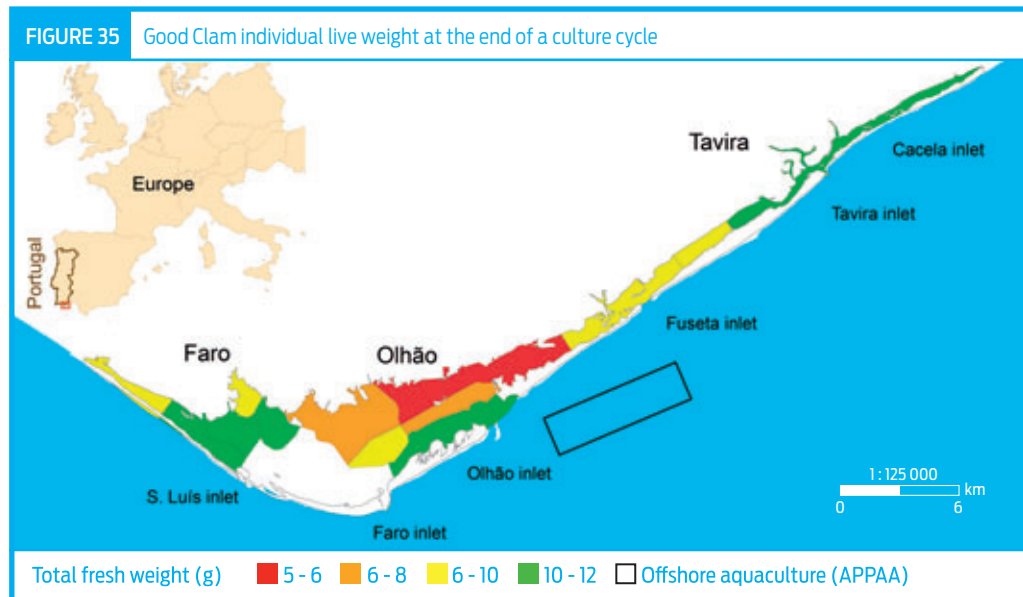
Another approach for this analysis is to compare the growth performance of an individual animal (Figure 35), which helps identify which areas of the Ria Formosa perform better in terms of growth. The model results indicate that the eastern part of the Ria is potentially the most productive, followed by the central area near the Armona inlet (Fortaleza), and the Faro area.

The simulation was executed with all the clam culture in place, so the variations in the individual weight already reflect food depletion due to the current aquaculture deployment.

However, in the model, a constant mortality rate is imposed on the cultivated bivalves, and this is an area for improvement. High summer mortality is common. A combination of low dissolved oxygen in hotter months, loss of condition due to spawning, and stronger symptoms of gill disease (dermo) due to the protozoan pathogen *Perkinsus marinus* apparently combine to cause high mortality.

Better data are required for identification of typical annual mortality patterns, and suggestions are made in the next chapter on ways to achieve this.

Simulations were made where the food available included not only the algae in the water column but also the microphytobenthos—a very conservative addition increases the annual clam harvest to 6700 tonnes. It is perfectly reasonable to accept values of double that tonnage, considering the microphytobenthos concentrations measured in the Ria Formosa.

FIGURE 35 Good Clam individual live weight at the end of a culture cycle

Total fresh weight (g) ■ 5 - 6 ■ 6 - 8 ■ 6 - 10 ■ 10 - 12 ☐ Offshore aquaculture (APPAA)

LOCAL-SCALE CARRYING CAPACITY

Open water aquaculture

Local-scale models are seen as a complement to ecosystem-scale models, as described earlier.

Farm-scale models have often been used for site selection and licensing purposes, but integrated coastal zone management should first make use of system-scale models for assessment of carrying capacity. The piecemeal approach of evaluating multiple sites ignores interactions, for instance food depletion in shellfish culture.

However, at a subsequent stage, farm-scale models provide a more detailed, and more accurate, assessment of site suitability, both in terms of production and environmental effects. Both types of models can be combined to carry out such an analysis. The system-scale model was run for a period of ten years, and data for
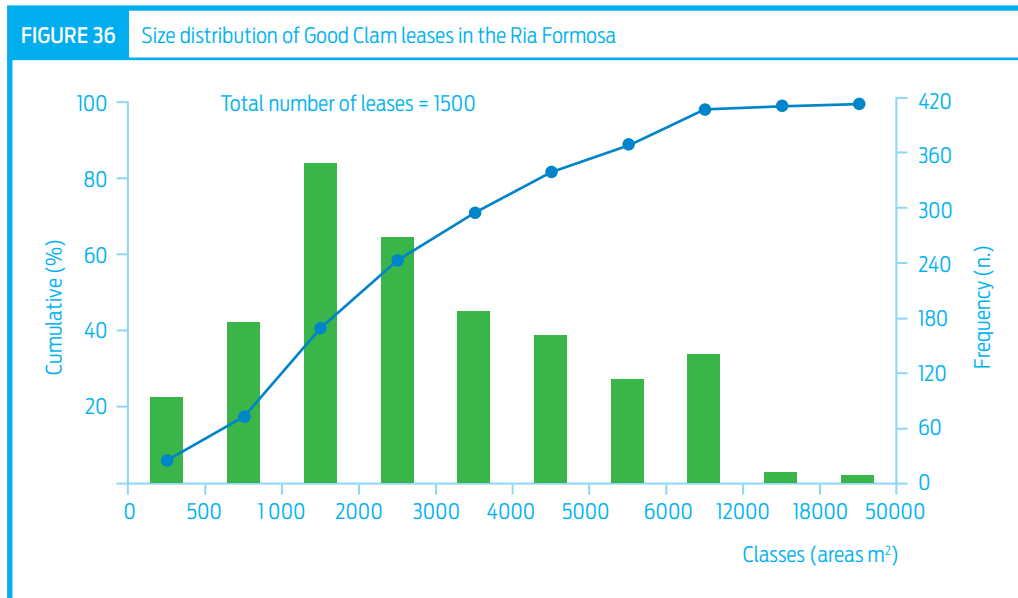
year seven were extracted with a frequency of 30 days in order to run the FARM model.

These environmental drivers were then combined with an analysis of the structure of the leases to select the median lease size (Figure 36), together with complementary input data such as current speed and cultivation density.

Since the food drivers supplied by the ecosystem model consider a depletion resulting from a full aquaculture situation, a factor of three multiplier was added to the pelagic algae to account for microphytobenthos as a food source.

Table 15 shows an analysis of production and environmental effects in three boxes (Table 14), selected due to their differing performance with respect to animal growth.

The farm-scale model can be used to assess the overall production, providing a comparison to the system-scale approach. If we consider the summed production in the farms in Table

FIGURE 36   Size distribution of Good Clam leases in the Ria Formosa

Total number of leases = 1500

| TABLE 15	Comparison of clam production and environmental effects in a standard lease (2000 m^2) at 3 different locations, with a culture density of 500 individuals m^{-2} and 30% mortality		
Box	TPP (tonnes)	APP	Profit (k€)
14	1.8	1.2	10
15	0.1	0.1	-11
18	7.3	4.9	75

15 for an aggregate area of 6000 m^2, i.e. 9.2 tonnes, and a cultivation period of 800 days, the overall annual clam production of the Ria Formosa is estimated as 3200 tonnes y^{-1}. Although this value is similar to the estimate from the system-scale model, it is merely indicative, since the FARM model does not account for interactions among culture sites.

Onshore aquaculture

A local-scale model was developed for onshore aquaculture, as a refinement of the FARM model, to which sediment diagenesis, natural and artificial aeration, and other factors were added.

The AquaFish individual model (Figure 37) was applied to the gilthead seabream *Sparus aurata*, which is cultivated locally. The model simulates feeding behaviour, with oxygen consumption due to basal metabolism, Specific Dynamic Action, and swimming, and other aspects of fish metabolism.

A fish production of 6.3 tonnes is obtained over a 420 day cycle, using 4 tanks with a combined area of 1 ha. A daily water intake rate of 3% of the total volume is applied, and the environmental externalities of finfish culture include a discharge of about 270 kg of ammonia and 7 kg of chlorophyll (algae) to the Ria.

FIGURE 37   FARM model mass balance for onshore gilthead culture in the Ria Formosa
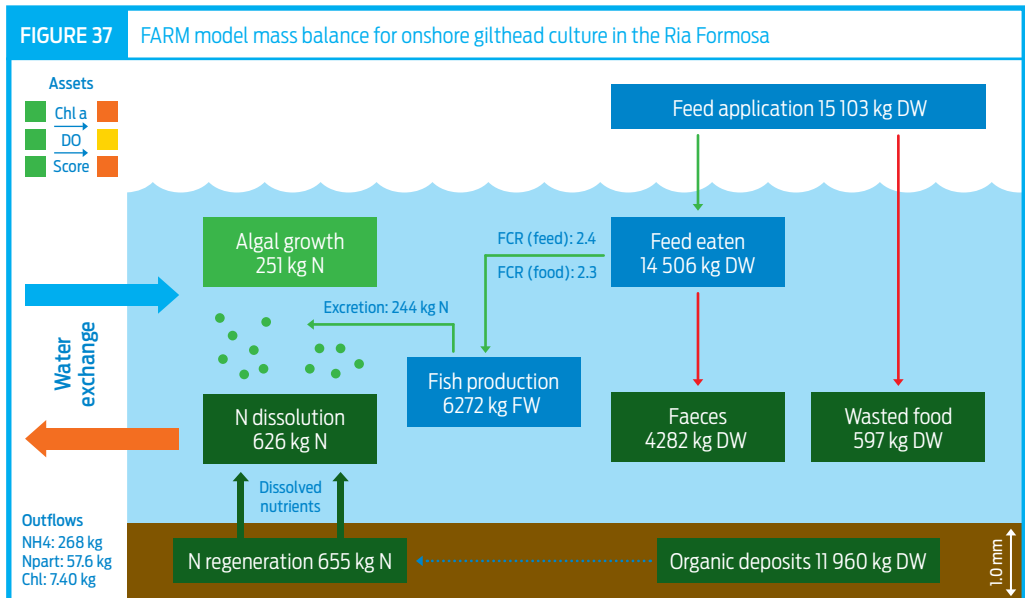
An application of the ASSETS eutrophication model to the culture cycle shows that the intake water, at good status (sensu WFD), is degraded to poor status at the outflow. This is illustrated by the percentile 90 for chlorophyll, which increases from 8 to 49 g L^{-1}, and the percentile 10 for dissolved oxygen, which decreases from 6.3 to 2.3 mg L^{-1}.

SOCIAL ASPECTS AND GOVERNANCE

Public participation

Currently, two of the principal pillars of aquaculture carrying capacity, the social and governance aspects, cannot be simulated using mathematical models. They are, however, fundamental to the sustainable development of aquaculture. Their role became apparent very early on in the FORWARD project, which led to a broadening of the project scope. Resolving one part of a problem is not the same as solving a problem.

These pillars probably correspond to over 50% of the integrated management of the Ria Formosa. The involvement of all interested parties right from the start was fundamental in addressing these components.

These entities were involved in the following areas:

Participation in regular meetings (11 meetings, including 4 plenaries, the FORWARD International Workshop in conjunction with the COEXIST project, and a final FORWARD presentation workshop) to report on progress, with ample scope for comments, criticism, and discussion;

Participation in fieldwork;

Analysis of all texts produced within FORWARD;

Press articles, interviews;

Participation of FORWARD team members in local events.

Discussion among stakeholders, a common understanding of terms and concepts, and the simple fact that opinions can be expressed during the decision-making process, are important contributions to consensus-building. That dialog provided, for instance, financial data for clam production (Table 17). The wage discrepancy between genders is perplexing, since it suggests that women can collect less clam seed, but it appears that there is no difference in harvesting. Participated governance plays a fundamental role in the sustainable future of aquaculture in the Ria Formosa.

TABLE 16	Identification of the FORWARD stakeholders	
Criterion	**Entities**	**Area of interest**
Legal mandate	Administration of the Algarve Hydrographic Region (ARH) Institute for Nature Conservancy and Biodiversity Directorate-General for Fisheries and Aquaculture	Management responsibilities, including planning, licensing, and oversight Responsible for the natural park, and delegation from ARH for aquaculture licensing Responsibilities in the licensing of aquaculture activities
Industry (Economic and social criteria	Growers associations Other associations	Direct involvement in aquaculture activities Connection to complementary or potentially conflicting areas
Others (Values, proximity)	University of the Algarve Press	Information about the Ria Formosa Information to the public

TABLE 17	Financial data on the production of the Good Clam				
	Price or cost	Seed collection	Maintenance and harvest	Harvest (kg/person)	
Sand	5-7 €/tonne*				
Gravel	14-15 €/tonne*				
Man (wage per tide)		50-60 €	40-60 €	15	
Woman (wage per tide)		40 €	40-60 €	15	
Licensed harvester	12 €/kg				
Unlicensed harvester	8 €/kg				
Imported from: USA, Morocco, Tunisia	~8 €/kg				
Imported from Spain	0.04 €/ind				
*Not including labour costs ~50 euros					

Barriers to entry

According to the EU Shellfish Waters Directive (2006/113/EEC), the waters of the Ria Formosa are considered as Class B; as such, shellfish products from the Ria Formosa require additional cleaning before they can be marketed. At present, six depuration plants exist, often playing an intermediary role, which may be a barrier with respect to product sale, since the depuration certificate is an essential part of the sale procedure.

Although the 'Good', or Algarve clams, are a high value product, there is no particular recognition of the origin of the clams, such as exists for wine regions throughout Europe, and food products such as cheese. A Ria Formosa brand should be promoted, perhaps as a sub-set of the Algarve brand name. Branding should be shown prominently on packaging, with an appropriate logo. Europe cannot compete on volume in the aquaculture market, so regional high value products must be placed by underscoring their origin, quality standards, and concerns with respect to sustainability.

Plot size and number, governance, mechanization

Many growers lease small farms, which is a management challenge. Some of the culture practices that are considered undesirable with respect to natural values are associated to the perception by farmers that each lease is an area that must be preserved spatially, and where production must be maximized—the lease value is considered to be dependent on these two factors. Consequently, plots are delimited by means of dividing markers such as bricks, ironwork or other objects. These separators play a dual role in clearly demarcating leases and preventing erosion.

Any tide pools within the leases are considered undesirable by the growers. These pools are formed naturally due to the irregular substrate, but since farmers wish to maximise the culture area, and the pools can easily become hypoxic or anoxic at low water, leading to mass mortality of shellfish, levelling is common, with drainage channels dug in the mud for outflow, just as in agriculture.

Mixed cohort plots are standard culture practice. This has several consequences, including (i) constant re-working of the sediment by growers; (ii) reduced possibilities for mechanized harvesting; (iii) mortality of larger, more fragile animals, in the post-spawning period can cause the death of later year classes (smaller animals) due to organic decomposition. There are diverging opinions on combined culture of year classes (up to three year classes). For instance in Puget Sound, USA, some farmers prefer co-cultivation, arguing that some of the waste products from larger Manila clams are used as food for the smaller animals. Others, however, use mechanized harvest to reduce labour costs and increase profits.

Farmers should be encouraged to experiment with alternative culture strategies, including mechanized harvest. This should be accompanied by extension workers from fisheries centres, and be tested in a precautionary manner. In order to explore this possibility, the legislation must be adapted appropriately, and leases cannot be below a certain size. Half a hectare (5000 m^2) would seem to be a minimum dimension for a part of a plot to be grown in year class strips.

Lack of certification

Clam culture practices in the Ria Formosa vary widely, and the whole industry would benefit from a more modern approach to cultivation, along the lines of the requirements set down by retailers such as Walmart or Wholefoods. The producer associations, local managers, and government agencies are keen to establish a certification program for the fishery.

Seed, juveniles and disease

Sources of seed are an issue for both clam and oyster culture. Natural seed beds exist for the Good Clam, but at present no hatchery or nursery facilities are available. Oyster seed in particular is supplied from hatcheries in France, Ireland, and elsewhere. It is very important to improve access to seed and juveniles, through the development of more flexible guidelines associated to better enforcement. There are presently no estimates of density or stock in the natural clam seed beds of the Ria, making it impossible to assess whether collection is sustainable.

Hatcheries are expensive, of the order of 100 000-1 000 000 €, and can be a commercial risk when natural recruitment is high, unless there is a clear downstream market for export of hatchery seed to other areas. Both public and private funding models have been used successfully, and an economic feasibility study, considering needs, markets, and financing, should be carried out. Nurseries, on the other hand, are a much lower expense (10 000-100 000 €), and enable the purchase of smaller, and therefore cheaper, seed, which is then reared and sold on for growout. In the United States, floating upweller systems, or FLUPSYs (Figure 7), have been highly successful for such a purpose.

Import of oyster seed from contaminated areas may lead to the emergence of diseases such as *Herpes*, it is critical to avoid the import of such seedstock. Strict veterinarian controls and traceability should be put in place to avoid further proliferation of shellfish diseases due to import of contaminated seed.

The industry should be united with respect to disease understanding and approaches, and an expert group should be established to advise on disease, including fisheries centres and veterinary professionals. An integrated, transparent disease monitoring scheme that involves stakeholders should be established. The use of hatchery reared/safe seed needs to be standard procedure, and research into pathogen management should be developed.

Farmers often shorten clam production due to mortality issues, limiting the cycle to a maximum of two summer periods, thereby losing the added value of larger animals (20-30 g live weight) harvestable only in third year. The mortality may be due to a number of reasons, most probably in combination, which have not to date been systematically analysed.

High summer mortality is common. A combination of low dissolved oxygen in hotter months, loss of condition due to spawning, and stronger symptoms of gill disease (dermo) due to the protozoan pathogen *Perkinsus marinus* apparently combine to cause high mortality.

HARMONISATION OF MULTIPLE USES

Marine spatial planning

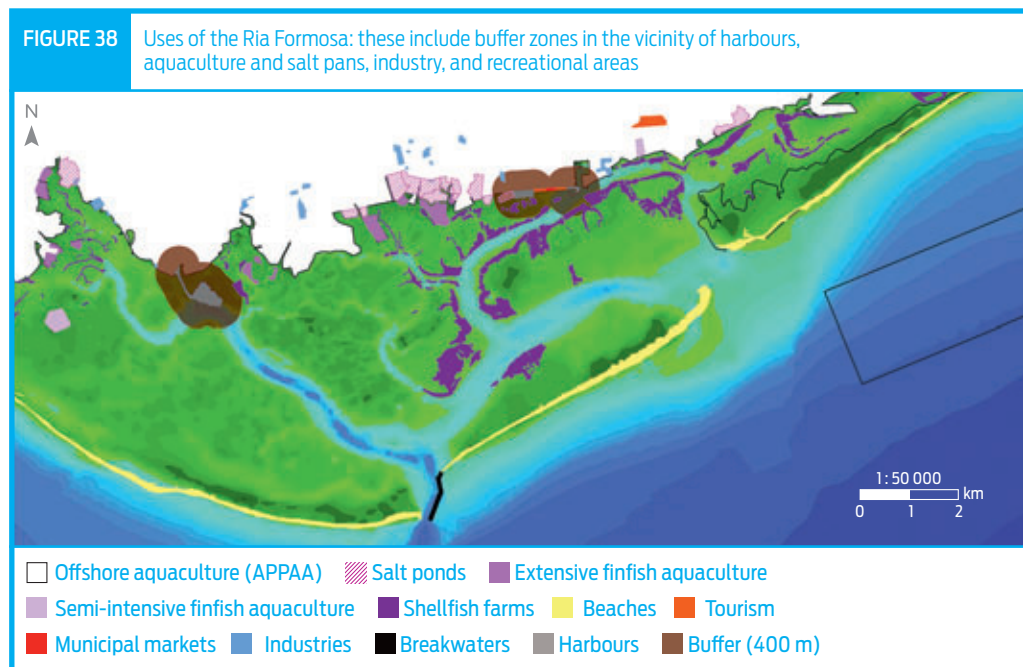Marine spatial planning is designed to identify the human activities occurring in marine areas, their interactions with each other and the ecosystem, and finally their potential conflicts and synergies. It aims to harmonise different uses and the development of activities without compromising ecosystem services, respecting environmental, economic and social objectives.

Interaction between aquaculture and nature conservation

Figure 38 shows fully protected areas in the Ria Formosa Natural Park and some farms located inside.

According to park regulaions, no use is allowed within such protected areas—there is therefore a usage conflict between the conditioned areas and the existing aquaculture.

To analyze the areas of influence, non-conflict buffer zones were drawn around the ports and marina areas (Figure 38). These areas are considered transitional and safety zones

FIGURE 38 Uses of the Ria Formosa: these include buffer zones in the vicinity of harbours, aquaculture and salt pans, industry, and recreational areas

☐ Offshore aquaculture (APPAA) ▨ Salt ponds ■ Extensive finfish aquaculture
■ Semi-intensive finfish aquaculture ■ Shellfish farms ■ Beaches ■ Tourism
■ Municipal markets ■ Industries ■ Breakwaters ■ Harbours ■ Buffer (400 m)

to avoid conflicts between recreational and commercial navigation, and the other activities. These include both direct conflict and associated processes such as erosion and contamination. Some of the farms are very close to this buffer zone and may be suffering from the influence of the shipping activities. These situations should be resolved within the context of the spatial plan applied to this coastal area.

In the planning process, spatial analysis can be combined with ecological models to explore alternative scenarios, e.g. changes to production, area, and/or culture practices of different cultivated species, taking into account the exclusion zones.

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GOING FORWARD – PILLARS FOR SUSTAINABLE DEVELOPMENT

Figure 39 illustrates the state of the art framework for carrying capacity analysis, where the central part provides the conceptual model, and the left and right sides indicate the limiting factors in the developed and developing world.

The future of sustainable aquaculture in the Ria Formosa depends on improvements to all of these components. We identify and discuss in this last chapter of the FORWARD book some of the areas that are critical for the next twenty-five years. Where such areas are amenable to mathematical modelling, examples are given. Where they are not, we suggest guidelines that should be integrated into policy.

FARM-SCALE OPTIMIZATION OF PRODUCTION

Data from system-scale models can provide environmental drivers for any area of the Ria Formosa. These data may then be used to drive local scale models such as FARM. These models can be used for marginal analysis, to determine optimal production densities. Such an analysis is shown below for EcoWin2000 model box 14 (Table 14 and Table 15), an area of intermediate productivity.

The marginal analysis (Figure 40) combines successive FARM model runs using increasing seed densities with the known values for input (P^i) and output (P^o) costs.
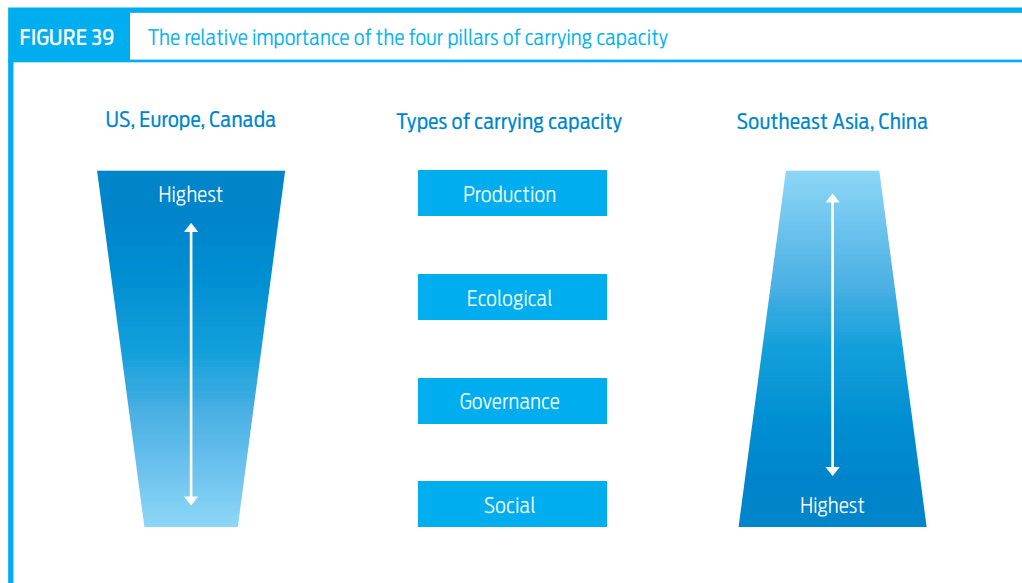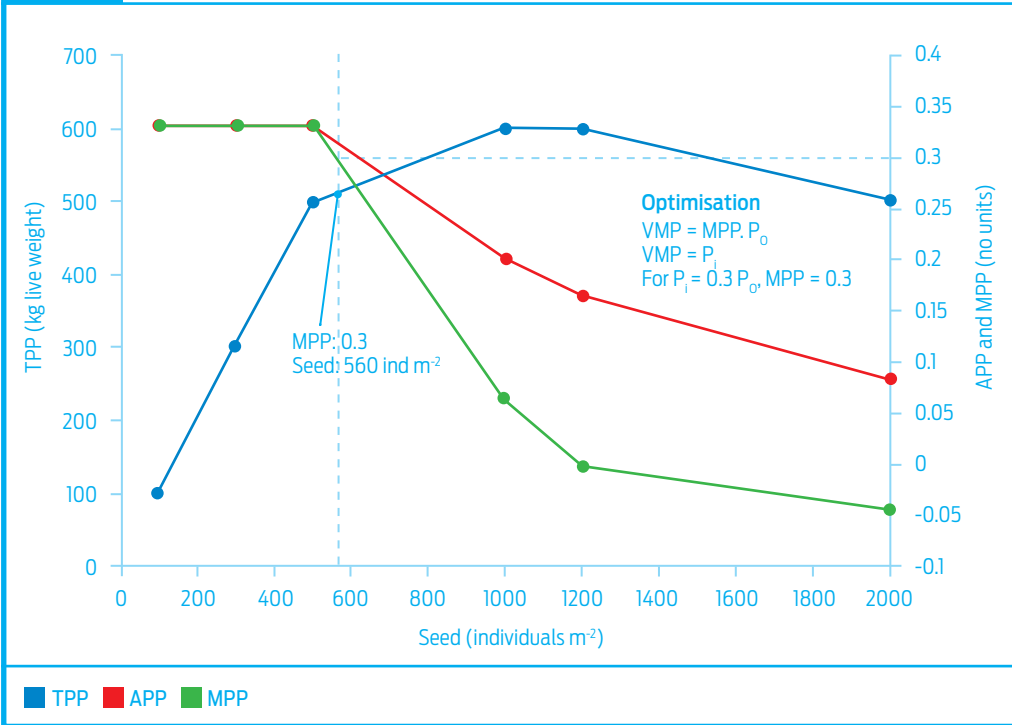
FIGURE 39 The relative importance of the four pillars of carrying capacity

US, Europe, Canada

Types of carrying capacity

Southeast Asia, China

Highest

Production

Ecological

Governance

Social

Highest

FIGURE 40 Marginal analysis for culture of the Good Clam, using the FARM model

Optimisation
$VMP = MPP \cdot P_O$
$VMP = P_i$
For $P_i = 0.3 P_O$, MPP = 0.3

MPP: 0.3
Seed: 560 ind m^{-2}

TPP (kg live weight)

APP and MPP (no units)

Seed (individuals m^{-2})

TPP   APP   MPP

The Value of Marginal Product (VMP) is used to calculate the marginal physical product (first derivative of the production curve) at which profit maximization occurs. In this example, that corresponds to a seeding density of 560 individuals per square metre.

Adjustments to culture density must however take into account mortality episodes. In order to gain a better understanding of this phenomenon, regular analyses of timing and spatial scale of mortality are required, to build up a multi-year (decadal) pattern of occurrence. Pre, during, and post-mortality analysis of temperature, dissolved oxygen, physiological status (gonad maturation and spawning) and *Perkinsus* levels. Study of correlations, trends, and interdependencies, and development of early warning monitoring systems and predictive models to provide advice to farmers, and training to the grower associations.

This will allow for early harvest and reduction of stocking density to avoid positive feedback of hypoxia due to decomposing organic material from dead animals. Such a system should be web-based, and not necessarily free of cost.

LINKS BETWEEN INSHORE AND OFFSHORE AQUACULTURE IN RIA FORMOSA

The addition of mussels to the offshore aquaculture area does influence the performance of clam leases within the Ria Formosa, with respect to production (Figure 41). A simulation of production of Mediterranean mussel in 30% of the offshore aquaculture area

FIGURE 41   E2K simulation of the annual harvest over a period of nine years, with and without the APPAA offshore aquaculture

■ Clam harvest with no offshore aquaculture   ■ Clam harvest with offshore aquaculture
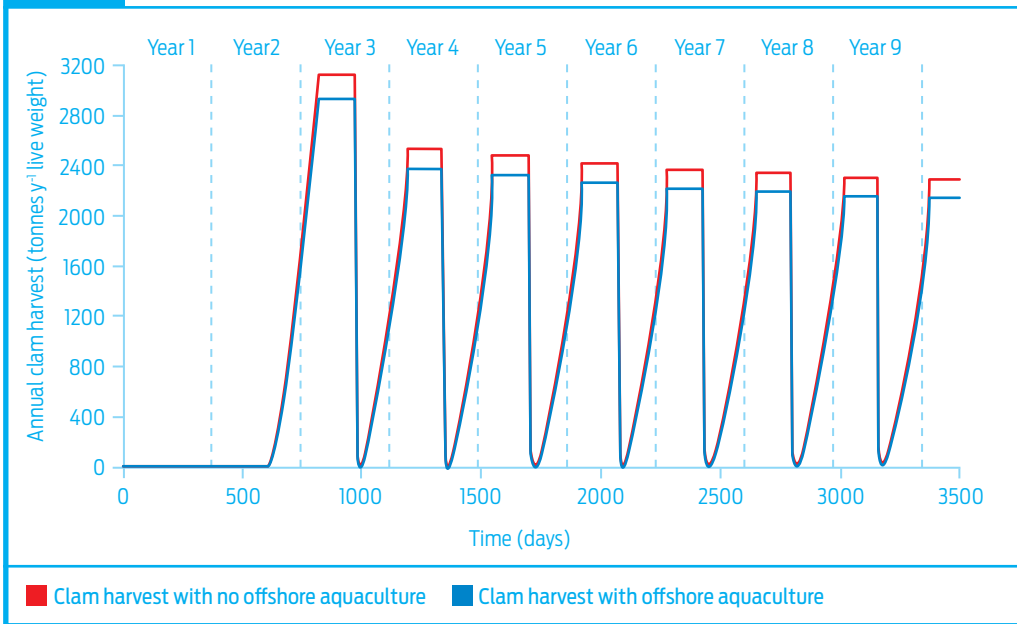
(APPAA) indicates that the expected annual harvest would be in the region of 13 000 tonnes. This suggests that this activity would be viable, at least from a growth perspective. Offshore aquaculture has many challenges, including structural stability, distance to port, and others.

The scenario of full mussel production at the APPAA reduces food availability to the clam beds, with a projected 120 tonne annual decline in clam production. This would be equivalent to a first sale loss of about 1 200 000 €, which may be offset by commercialisation of mussels.

Stakeholder awareness of this trade-off is very important. Model results should always be viewed as a support to decision-making, not an absolute truth. Despite this caveat, the ecological model is certainly sensitive to the introduction of a large cultivation area offshore of the Ria Formosa clam beds, and

provides a first order assessment of impact. Further work integrating the finfish culture component should be carried out. This is beyond the scope of FORWARD, but will help understand (i) what the role of integrated multi-trophic aquaculture (IMTA) will be in mitigating food depletion for co-cultivated shellfish; (ii) to what extent particles emerging from fed aquaculture and fish waste may be relevant as a food source for clams within the Ria.

From a production perspective, both inshore clam culture and offshore mussel culture can coexist, but a thorough assessment of the disease implications of the two culture areas and their interaction should be carried out. Work is ongoing in the COEXIST project on models to help inform this issue, and these may be integrated in the system-scale EcoWin2000 model if this research is successful. The relevance of potential disease threats both (i) within the separate inshore area (where

FIGURE 42 Change in Good Clam production in the Ria Formosa with the addition of mussel culture in the APPAA
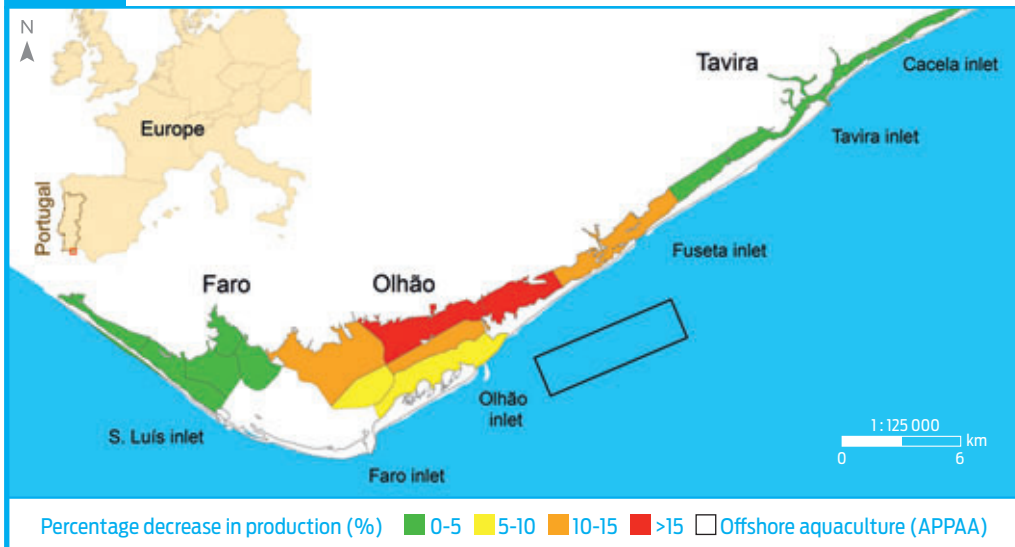
Percentage decrease in production (%) ■ 0-5 ■ 5-10 ■ 10-15 ■ >15 □ Offshore aquaculture (APPAA)

Perkinsus seems to be already endemic) and within the offshore area (where close co-cultivation requires a clear, appropriate, and strictly enforced disease policy); and (ii) between the two areas, cannot be understated.

Spawning from shellfish cultivated in the APPAA is an additional concern: it may lead to high biomasses of competing bivalve species, such as mussels, in the Ria Formosa, and to increased fouling of fish cage nets, both within the APPAA and elsewhere.

Case studies 2 and 3, included in the final part of the FORWARD book, contribute to this analysis.

INTEGRATED MULTI-TROPHIC AQUACULTURE (IMTA) IN ONSHORE PONDS

Some aspects of IMTA were already addressed above, in the context of the Armona offshore park. Another application of integrated multi-trophic aquaculture is in the optimization of

land-based finfish culture, through co-cultivation of bivalves.

Table 18 illustrates the difference between gilthead monoculture and polyculture with oysters in IMTA. Combined finfish and bivalve cultivation has considerable advantages over monoculture: food available for oysters increases significantly in IMTA, leading to a marked increase in production—from 7 kg to almost one and a half tonnes. Income increases by 50%, due to the additional production of bivalves, even if we neglect the ecosystem services they render. The ASSETS eutrophication index changes from poor to moderate, and although ammonia emissions double in IMTA due to oyster excretion, algal emissions (chlorophyll) in the effluent are reduced to 20% when compared to gilthead monoculture.

VERTICAL INTEGRATION OF AQUACULTURE

Depuration centres

The role of depuration centers needs to be clarified; depuration will become unnecessary as

TABLE 18	Production, environmental effects, and income of different aquaculture alternatives simulated with the FARM model		
Indicator	**Monoculture (Oysters)**	**Monoculture (Gilthead)**	**Integrated aquaculture (Gilthead + oysters)**
Individual weight (g)	39	329	329 + 71
Production (kg cycle^{-1})	7	1860	1860 + 1423.5
APP	0.07	74	74 + 14
Primary production (kg N cycle^{-1})		201	61
Discharge to the Ria			
Ammonia (kg cycle^{-1})		97 (50%)	194
Chlorophyll (kg cycle^{-1})		6.9 (500%)	1.4
ASSETS (eutrophication)	▬	▬	▬
PEQ removed	3	-	6
Income (euros)	155	9303	9303 + 4224

Notes: cycle: 650 days; area: 1 ha (4 ponds); water intake: 150 m^3 d^{-1} (3% of volume); culture density: 0.5 gilthead m^{-2}, 5 oysters m^{-2}

the water quality of the Ria Formosa improves to reach Class A, but the depuration certificate can reassure the consumer as an additional health safeguard. The public administration must ensure that clam and oyster farmers have unrestricted access to depuration facilities at a fair price, and are in no way constrained to sell their product to depuration plants.

Certification

Consumers display an increasing awareness about the production of the food they purchase, not only in terms of quality and safety but also environmental impact, social responsability, and animal welfare. The development and implementation of a certification process may promote consumer confidence in aquaculture products and contribute to improve culture practices.

Good culture practices

Best practice codes in aquaculture management may become extremely useful instruments, that ensure farms do not have serious negative environmental effects on the surrounding environment.

The Strategy for Sustainable Development of European Aquaculture developed by the European Union in 2002, proposed several actions, including the establishment of transnational codes of conduct. These should be initiated by the industry, and be based on the 1995 FAO code of conduct for responsible fisheries, together with the elaboration of best practice codes. The objective is to assure consumers that the products supplied by growers that adhere to these codes fulfil adequate safety and environmental criteria.

The development and implementation of codes of conduct and best practice is an important step towards responsible management. When the principles and rules of such codes include environmental, social, and economic aspects, their application may constitute a sound basis for sustainable aquaculture. They allow environmental goals for the maintenance of water

and ecosystem quality to be achieved, and represent a mutual benefit between aquaculture production and protection of natural resources.
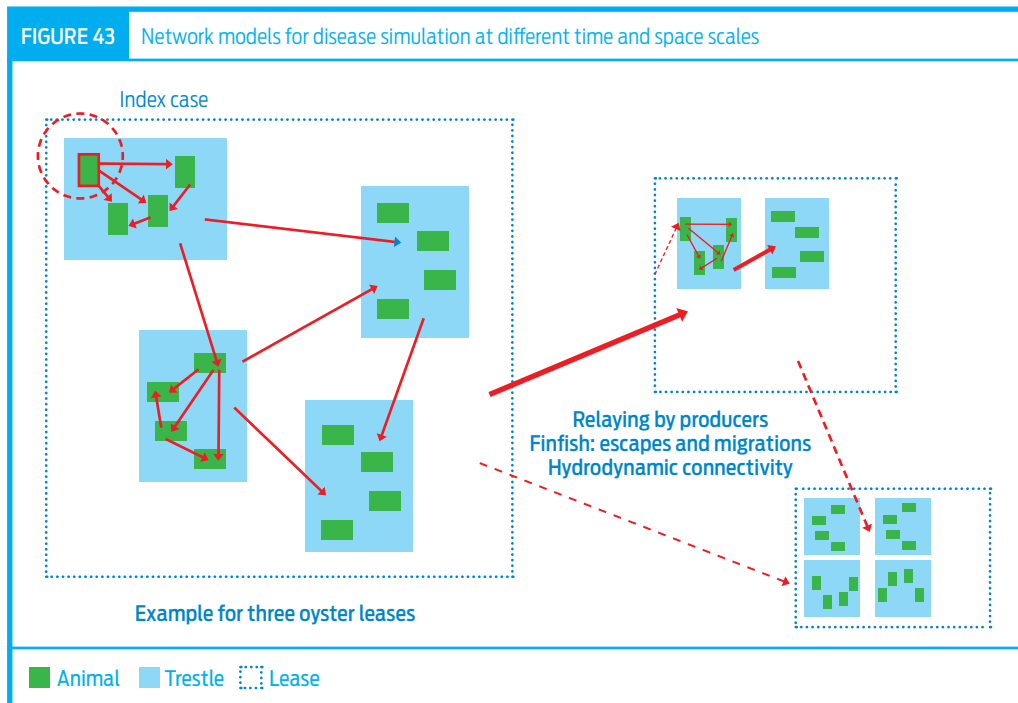
Basic principles for certification

Certification must be transparent, providing access to information and participation to all interested parties; the certification process should also benefit the growers, rewarding them economically for their efforts; certification should be voluntary and open to all producers; certification should be:

| Multi-sectorial

| Environmentally acceptable

| Socially equitable

| Economically viable

Since about 80% of the clams currently produced are exported, and since this market can potentially still grow, particularly in value, and since there is additional growth potential for other species such as oysters, the industry has every reason to adopt international certification procedures, which in turn will increase export demand.

The industry must be co-opted in a process of this kind, both at the level of growers and their associations. The process initiated during the FORWARD project should be continued; much depends on the acceptance and initiative of producers, together with the stimulus from public institutions.

The FORWARD project researched the various options, and proposed that Global GAP should be selected as a certification body. This was based on the type of product offering, pricing,

FIGURE 43 Network models for disease simulation at different time and space scales

Index case

Relaying by producers
Finfish: escapes and migrations
Hydrodynamic connectivity

Example for three oyster leases

■ Animal ■ Trestle ⬚ Lease

and accessibility. A website was registered and developed (http://goodclam.org/ certify/) to allow producer associations to complete and submit certification documents. A subsequent inspection by the certification agency will identify shortcomings, and after these are addressed, it will be possible to certify a culture area.

Producer associations must prepare for certification by providing guidance to their asscociates on more sustainable culture practices. Both individual growers and the community at large will benefit from the increased recognition of quality, brand certification, and a more significant participatory role in the value chain. The industry needs to be stimulated to reach this goal, moving away from some of the traditional practices; the associated extension work is undoubtedly a key task of the regional fisheries and support agencies.

DISEASE CONTROL

In determining the carrying capacity of aquaculture operations, it is important to ensure aquaculture production practices and systems within a farm, managed region, or zone, are resilient to the effects of disease. Modeling provides a means of investigating the interactions occurring among the four pillars of carrying capacity, and the spread and establishment of pathogens; however, to date most models have ignored the influence of society on aquatic disease. Many different models have been derived to investigate the spread and impact of particular pathogens: in aquatic systems two of the most common approaches are (i) compartment-based models; and (ii) network models (Figure 43).

The main objective of these models is often to track disease through a population of animals, but they have also been applied to look at spread through a population of sites. Simple

implementations are often analytically tractable, allowing conditions under which thresholds and equilibria occur to be found without the need to run simulations.

One of the key pieces of information that can be derived from these models is a maximum (susceptible) host carrying capacity for which a pathogen cannot persist. Such carrying capacities used in the context of pathogens are often referred to as a critical threshold, and may be useful to wildlife and farm managers when attempting to control or prevent disease.

GOVERNANCE

Lease restructuring

It appears necessary to restructure the licensing scheme, to reduce the number of leases and increase unit size. This should be done gradually as leases expire, and be fully discussed with industry associations. Larger leases will be less vulnerable to marginal erosion with respect to the total lease area, and substrate losses in one part of the lease may be compensated by sediment deposition in other parts of the lease. This will remove the requirement for the use of extraneous objects such as bricks to attempt to consolidate substrate. Since these objects are also used to delimit small plots, this will also become unnecessary. Larger leases will reduce capital costs, and potentially allow an increased degree of mechanization, lowering labour costs. A reduction in the number of stakeholders may also improve the effectiveness of collective decision-making.

Best management practices

Local management entities

The entities most directly involved with the management of the Ria Formosa, whether in water management, nature conservancy,

or aquaculture and fisheries, must work in closer proximity with the end-users, and promote greater participation in decision-making processes.

Future actions

Change the concept that aquaculture is harmful to the environment; provided the principles of sustainable development are respected, aquaculture contributes to food security, economic growth, job creation, recovery of fish stocks, and preservation of wild species;

Develop aquaculture through improved planning, in order to harmonize the multiple uses of the Ria Formosa;

Maximise potential production and optimise the performance of sustainable aquaculture practices, making the most of natural resources in the Ria Formosa;
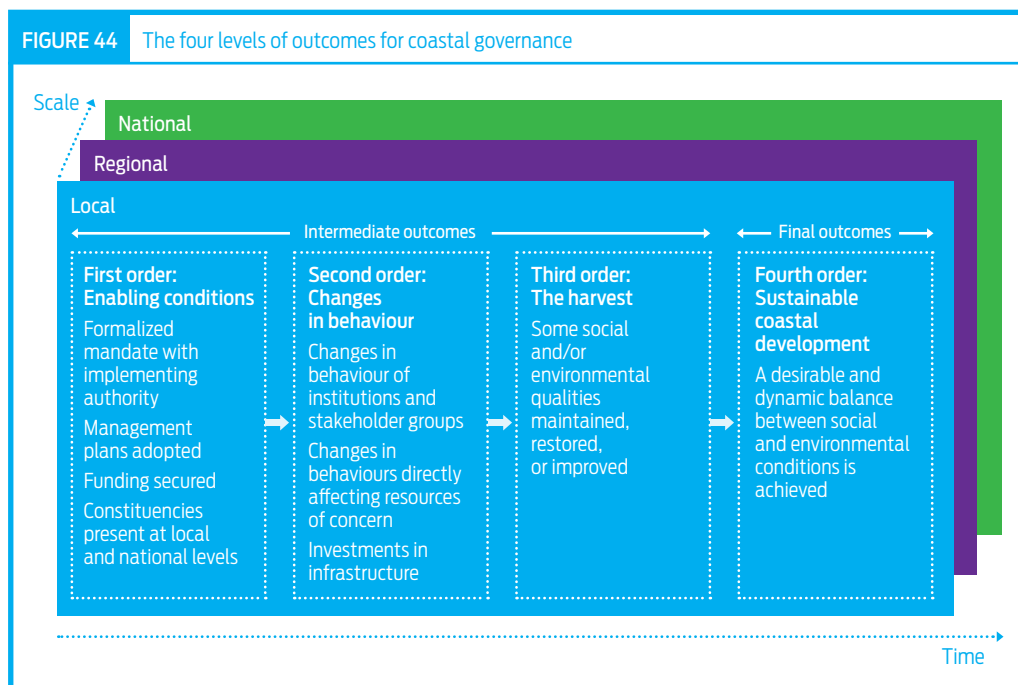
Tailor applied research towards innovation and technical and scientific support of aquaculture;

Improve the coordination among the various legislative and scientific instruments, both public and private, that affect the sustainable development of aquaculture;

Improve coordination across a range of government bodies responsible for fisheries and environmental affairs, in order to set up a dialog between government and industry, to resolve the bottlenecks that have hampered aquaculture development.

It is essential to reinforce the partnerships between the production sector and the research institutions which can provide specialized knowledge to the aquaculture industry. These partnerships must focus on the increase and diversification of aquaculture production, innovative production processes,

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FIGURE 44	The four levels of outcomes for coastal governance

Scale

National

Regional

Local

← Intermediate outcomes → ← Final outcomes →

First order: Enabling conditions
Formalized mandate with implementing authority
Management plans adopted
Funding secured
Constituencies present at local and national levels

Second order: Changes in behaviour
Changes in behaviour of institutions and stakeholder groups
Changes in behaviours directly affecting resources of concern
Investments in infrastructure

Third order: The harvest
Some social and/or environmental qualities maintained, restored, or improved

Fourth order: Sustainable coastal development
A desirable and dynamic balance between social and environmental conditions is achieved

Time

product qualification and promotion, and improvement of culture practices, in order to enhance sectorial sustainability.

Field training on technical aspects, and dissemination of the most appropriate technologies for the different needs of the aquaculture sector, are also recommended.

Measures for the development of bivalve culture

- Re-evaluate of the regulations that apply to aquaculture in the Ria Formosa, in order to introduce greater flexibility, and simultaneously improve compliance;

- Define an incentive scheme to avoid levelling of tide pools and channels;

- Limit culture density to avoid high mortality;

- Perform growth trials with and without the application of pebbles and gravel;

- Examine effects of gravel on predation by fish, consider using predator nets

- Involve the growers, through industry associations, in a social contract with respect to the regulations to be applied;

- Improve oversight mechanisms in order to assess compliance;

- Introduce hatcheries and nurseries for use by the growers;

- Regulate recreational fisheries in the Ria Formosa, and in particular shellfish collection, so as to avoid conflicts with professional growers.

Main findings and recommendations of the FORWARD project

The table below lists the main findings and recommendations of the FORWARD project. These twenty-one points, which are developed in the Executive Summary and analysed in detail in the different chapters of this book, focus on specific aspects that the authors believe should form the basis for the sustainable management of the Ria Formosa and adjacent coastal area.

The combination of a full environmental analysis, supported by the range of mathematical models developed and applied in FORWARD, with the development of the governance aspects described above, will allow the Ria Formosa to become a more sustainable system, following the model shown in Figure 44.

The training of local technicians in the suite of models provided by FORWARD is an essential element for the successful legacy of this programme.

In the Ria Formosa, as elsewhere, more sustainable aquaculture will depend on improved resource use, greater respect for the ecological balance of the system, better social equilibrium, and fully participative governance.

Many of the lessons learnt in this project are relevant for the development of sustainable aquaculture in Portugal, Europe, and the world. The results obtained in FORWARD, and set out in the pages of this book, furnish a blueprint for a better future.

TABLE 19	Main findings and recommendations of FORWARD
Finding	**Recommendation**
Social and governance aspects are not amenable to mathematical modeling.	Appropriate governance plays a major role in a sustainable future for aquaculture in the Ria Formosa.
First sale revenue determined for a clam production of 5000 tonnes per year is 50 million euros.	Improved socio-economic analysis analyse the overall GDP of the Ria Formosa, including capture fisheries, aquaculture, salt extraction, and tourism.
Six depuration plants exist, often playing an intermediary role, which may be a barrier with respect to product sale, since the depuration certificate is an essential part of the sale procedure.	Public administration needs to ensure that clam and oyster farmers have unrestricted access to depuration facilities at a fair price, and are in no way constrained to sell their product to depuration plants.
No particular recognition of the origin of the clams.	Ria Formosa brand should be promoted, perhaps as a sub-set of the Algarve brand name.
The existence of many growers and very small leases creates a management challenge for management of lease areas.	Restructuring of licensing scheme, to reduce the number of leases and increase unit size.
Mixed cohort plots are standard culture practice. This has several consequences, including (i) constant re-working of the sediment by growers; (ii) reduced possibilities for mechanized harvesting; (iii) mortality of larger, more fragile animals, in the post-spawning period can cause the death of later year classes (smaller animals) due to organic decomposition.	Farmers should be encouraged to experiment with alternative culture strategies, including mechanized harvest. This should be accompanied by extension workers from fisheries centres, and be tested in a precautionary manner.
The whole industry would benefit from a more modern approach to cultivation.	Global GAP should be selected as a certification body. See details on http://goodclam.org/
Microphytobentos may be an important food source for clams and oysters.	Further research work is needed, focusing specifically on the food source issue, in order to clarify the role of pelagic and benthic algae as drivers of clam and oyster growth.
Sources of seed are an issue for both clam and oyster culture. Natural seed beds exist for the Good Clam, but at present no hatchery or nursery facilities are available. No estimates exist of density or stock in the natural clam seed beds of the Ria.	Improve access to seed and juveniles, through the development of more flexible guidelines associated to better enforcement. Evaluate the stocking density and area of natural seed beds to enable sustainable collection. The development of hatcheries and in particular nurseries should be analysed and if possible promoted.
Import of oyster seed from contaminated areas may lead to the emergence of diseases such as *Herpes*.	Strict veterinarian controls and traceability to avoid further proliferation of shellfish diseases due to import of contaminated seed.
Combination of low dissolved oxygen in hotter months, loss of condition due to spawning, and stronger symptoms of gill disease (dermo) due to the protozoan pathogen *Perkinsus marinus* apparently combine to cause high summer mortality.	Regular analysis of timing and spatial scale of mortality, to build up a multi-year (decadal) pattern of occurrence. Predictive tools will allow for early harvest, and reduction of stocking density to avoid positive feedback of hypoxia due to decomposing organic material from dead animals.
Growth of opportunistic seaweeds such as *Ulva*, and seagrasses such as *Zostera*, can severely reduce dissolved oxygen concentrations at night-time low tide.	Regular mechanical mulching should be implemented, particularly in periods of peak fouling. For *Zostera*, removal should be analysed on the basis of the conservation status of specific species. Application of artificial substrates such as gravel should be discouraged.
There is a perception that lack of sewage treatment and irregular operation of wastewater treatment plants (are the main sources of pollution. However, approximately 50% of nitrogen load that reaches the lagoon via the watershed is due to diffuse pollution.	Identification of mortality episodes during/after periods of high precipitation. Conditioning or interdiction of harvest during and after high rainfall events and storms, or additional depuration, to ensure microbiological quality is adequate. Use of appropriate microbiological indicators to distinguish between point and diffuse sources.

Finding	Recommendation
Shellfish density may be too high for the low concentration of food in the water column, particularly during the ebb. Nutrient discharges to the Ria Formosa do not lead to high phytoplankton biomasses within the Ria, because the water residence time is too short for bloom formation.	Based on model results, experiments should be conducted in selected leases, to assess the effects of food supply on clam production and mortality. These experiments should consider different age classes (cohorts) and be extended over one year, to include the summer period when the animals are most fragile.
The main nutrient sources for the Ria are, in equal parts, loads from WWTP (45% N, 32% P) and diffuse loads from agricultural fertilization (55% N, 68% P). The WWTP network has experienced significant improvements and can be considered adequate.	The focus of studies and controls on watershed loads should move from WWTP to agricultural sources. There is still insufficient knowledge on diffuse contamination processes, and more information is required, particularly streamflow nutrient concentration measurements in peak flow periods, and studies on aquifer contamination and coastal interaction processes.
EcoWin2000 (E2K) ecological model, validated for standard conditions, provides a total clam harvest of about 2300 tonnes per year. There is a wide variation in individual clam growth, and in the yield per unit area within the Ria Formosa.	Once set up, the E2K model is simple (Excel-like) and fast (about 15 minutes for 10 years) to run. Local managers should be trained in its operation, with the aim of testing various alternatives to cultivation, including reduction of seed density in areas of lower yield.
Simulation of mussel culture for the APPAA offshore aquaculture area returns a harvest of 5000 tonnes per year.	Detailed application of the ecological model can provide more specific analyses on a per-lease basis, and be used to test interactions among leases with respect to food depletion.
Addition of mussels to the offshore aquaculture area does influence the performance of clam leases within the Ria Formosa, with respect to production, with a projected 120 tonne annual decline in clam production.	Stakeholder awareness of this trade-off is important. Further work integrating the finfish culture component should be carried out.
Inshore clam culture and offshore mussel culture can coexist from a production perspective.	Thorough assessment of the disease implications of the two culture areas and their interaction should be carried out. The relevance of potential disease threats both (i) within the separate inshore area (where *Perkinsus* is already endemic) and within the offshore area (where close co-cultivation requires a clear, appropriate, and strictly enforced disease policy); and (ii) between the two areas, cannot be understated.
EcoWin2000 model adequately simulates production, but the mortality component needs to be improved. This is largely due to inadequate data on mortality, added to the fact that the timing and causes of mortality events are insufficiently understood.	Better understanding of mortality, using risk-based approaches as recommended above, can lead to tools that can be integrated with the E2K model (or others) to trigger mortality events and reproduce observed patterns.
Simulation of clam production in intertidal areas is a practical way of assessing suitability. Local-scale simulations of pond culture may help in determining finfish culture density, and appropriate combinations of finfish and shellfish in IMTA.	The FARM model is available to the local water resource and fisheries managers, and through them to the growers' associations for use by farmers. Both the onshore and inshore culture can be examined. The environmental drivers for both the shellfish and finfish models can be taken from existing data or from simulations using the system-scale model.

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CASE STUDIES

In the final part of this book, as a complement to the FORWARD work, various specialists were invited to contribute four short case studies. The intent was to discuss aspects relevant to the Ria Formosa, but broad enough to be of general interest. The first case study examines issues related to sediment transport; the second presents results on the application of an ecological model to study the production and economic potential of the Armona offshore aquaculture area. A review of disease issues in aquaculture follows, and the final case study examines the success story of the largest shellfish aquaculture company in the United States.

CASE STUDY 1: HYDRODYNAMICS AND SEDIMENT TRANSPORT PATTERNS

Tidal inlets

The Ria Formosa is a highly dynamic multi-inlet barrier island system characterised by a complex network of natural and partly dredged channels.

The shape of the Ria Formosa produces two areas with different exposure to wave action: the western side, under the direct influence

FIGURE 45 Ria Formosa inlets and adjacent channels: (A) tidal prism and (C) residual discharge at spring tides; (B) tidal prism and (D) residual discharge at neap-tides.
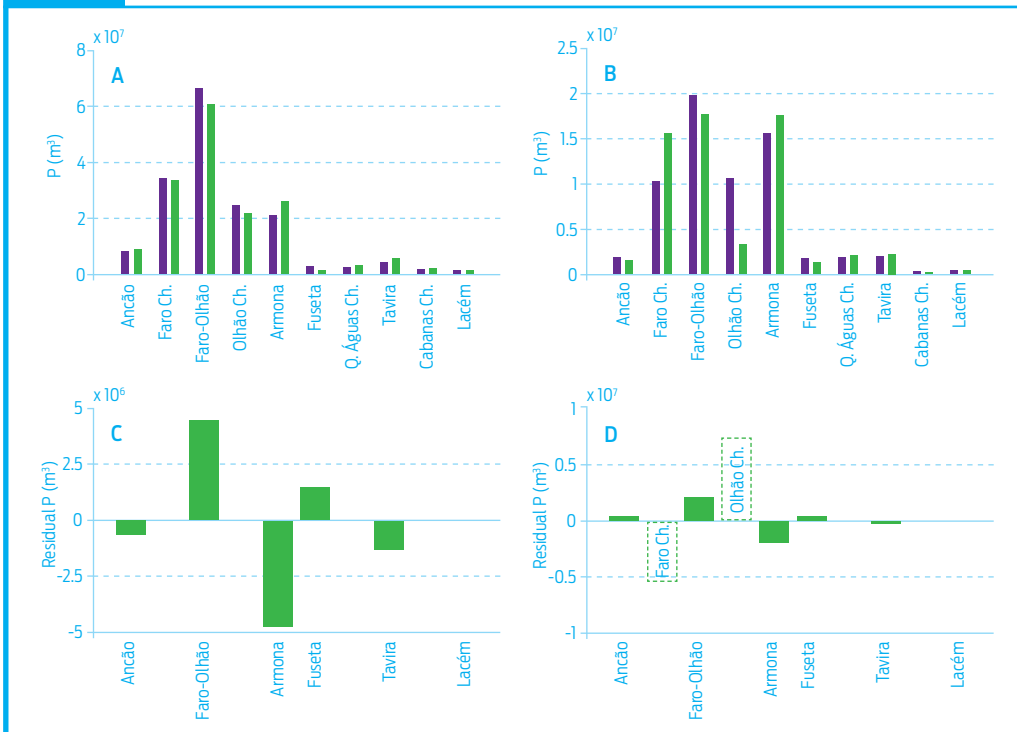
of the dominant SW wave conditions, is more energetic, while the eastern side is directly exposed only to SE waves. The multiple tidal inlets are hydrodynamically connected, and therefore a morphological change in a given inlet could modify the water circulation of other inlets and adjacent channels. These changes are, in general, a function of tidal prism, which is a measure of the water exchange through the inlet. When a new inlet is opened and stabilised, its tidal prism will increase until it reaches equilibrium between its cross-section and the volume of water flowing through the inlet.

Morphological changes can occur in areas adjacent to the new inlet over years to decades, and coastal response to engineering stabilisation may extend far updrift and downdrift of the inlet. In a multiple tidal inlet system the changes can be more dramatic because the current field will change completely, inducing short and long-term impacts on water circulation through the other inlets.

The existence and persistence of multiple tidal inlets in coastal systems is fundamental for flushing capability, navigability, and beach/barrier stability, as these depend on factors not found in single-inlet systems.

The capacity of a back-barrier system to maintain multiple inlets depends largely on the sediment transport pattern in the vicinity of each inlet. If the littoral drift is strong, ebb shoals trap significant quantities of sand.

The combined current-wave interaction during storm events forces morphological changes so that the inlet can move from an essentially tide-dominated condition to a wave-dominated condition. During such events, the tide may not have the capacity to transport the material away from the inlet mouth area, and the inlet will accumulate sand due to the migration of the shoals to the shore.

Water circulation and sediment transport patterns

Measurements of the tidal prism performed between 2006 and 2007 for each inlet of the Ria Formosa reveal a clear circulation pattern between Faro-Olhão and Armona inlets (Figure 45).

The two inlets present ebb-dominated behaviour (i.e. higher mean ebb velocity is associated with shorter ebb duration). However, at the Faro-Olhão Inlet, the flood prism is considerably greater than the ebb prism. The sediment transport direction is strongly landward directed as evidenced by the regular dredging operations required to maintain channel navigability. In contrast,

FIGURE 46 (A) Ancão Inlet in 2006: inlet opening position (inlet relocated artificially in 1997);
(B) limits of the topo-bathymetric survey performed during 2006;
(C) limits of the topo-bathymetric survey performed after the storm of March 2010, with the new eastward inlet position leading to the closure of the former one
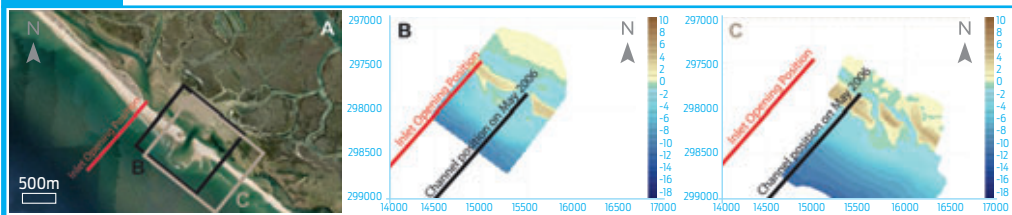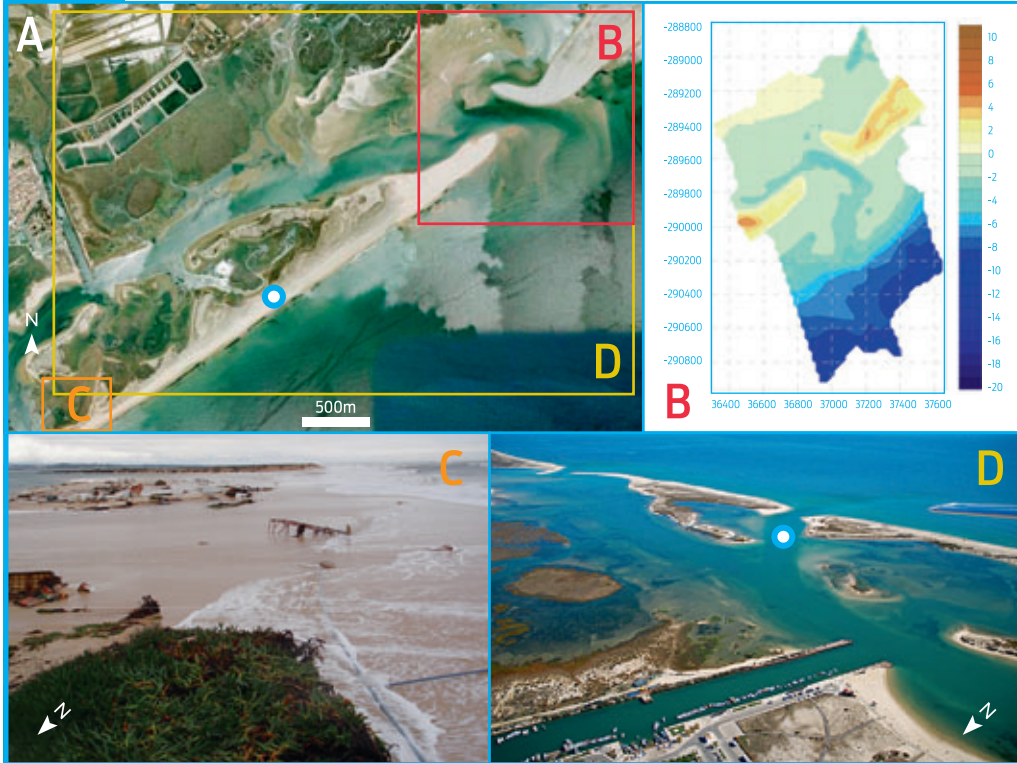
FIGURE 47 (A) Fuseta Inlet in 2006, showing topo-bathymetric survey limits from May 2006; (B) overwashing of the barrier due to a storm in March 2010 and opening of a new inlet westward; (C) artificial closure of the new inlet breach and (D) new artificial relocation (marked with a star); the old inlet remained open and was later closed by coastal authorities

the Armona Inlet is always ebb-dominant and capable of flushing sediment seaward under fair-weather conditions, especially during spring tides. These two major inlets represent almost 90% of the total prism of the Ria Formosa.

The interconnection between both inlets is particularly active during spring tides, but is reduced during neap-tides when the inlets drain the basin more independently.

Although the largest morphological changes occur during storm events, the day-to-day interception of the longshore-transported sand, and its passage through and past an inlet, is governed by fair-weather hydrodynamics. Estimates of sediment transport collected under prevailing fair-weather conditions reveal net export of sediments at Ancão, Armona, Fuseta and Tavira and net import at Faro-Olhão and Lacém inlets.

Despite the capacity of the inlets to redeposit sediments offshore under fair-weather conditions, net sediment influx during increased periods of combined current-wave interaction during storms can reduce the hydraulic efficiency of the channels. Episodic events (i.e. storms) can open natural inlets through the system and observations show the system's ability to maintain those inlets open through

FIGURE 48 (A) Location of the artificially-opened Faro-Olhão Inlet (prior to opening, superimposed on a 1923 map); (B) Evolution of Culatra Island from 1945 to 2009; (C) Faro-Olhão Inlet channel in 1948 and (D) 2006, showing intense scouring at the inlet gorge; (E) Armona Inlet width evolution
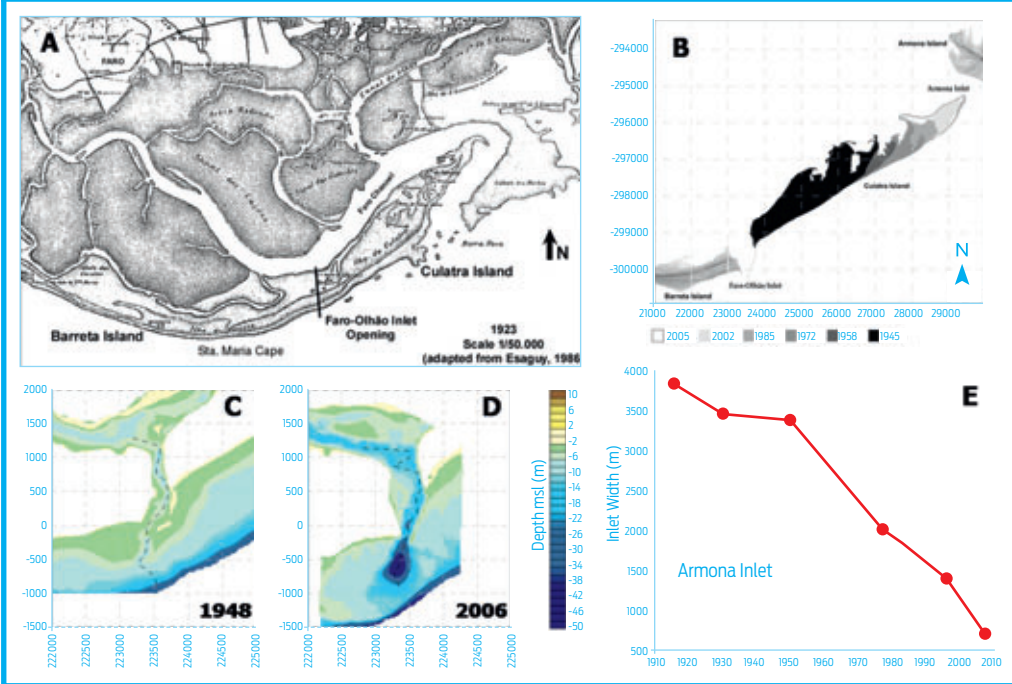
periods of variable length. This happened recently at two inlets of the system: Ancão (Figure 46) and Fuseta (Figure 47).

At the first site a migration was forced by jump, with a natural closure of the westward inlet and persistence of the new inlet; at the second site, a westward opening developed in a more natural and favourable position, which forced a series of engineering interventions in the system.

Morphodynamic evolution as a result of human interventions

The Ria Formosa has been the subject of human activities with marked and/or unknown changes to the adjacent coast. An analysis of the area's evolution, from the XIVth century

until the present day, shows that although the system has historically responded to both natural and artificial disturbances, with significant changes in overall morphology, it has always maintained between 4 and 7 inlets.

The most recent major change to the system resulted from the opening of the Faro-Olhão Inlet, which captured a large tidal prism from the Armona Inlet, formerly the dominant natural inlet in the system. The Faro-Olhão Inlet opening illustrates the unpredictable effects of anthropogenic intervention.

The Faro-Olhão Inlet, the main inlet of the Ria Formosa system, was artificially opened in 1929 at the location of the old Bispo Inlet (Figure 48A), approximately 2 km east of Cape Santa Maria. The objective was to ensure the

maintenance of navigable depths in the access channel (i.e. the Faro Channel (Figure 48A), leading to the two most populated areas, Faro and Olhão. Two jetties were built to protect the access channel from the prevailing west-to-east littoral drift and to improve navigational aspects, in particular the depth and orientation of the Faro Channel. However, the distance between the jetties (160m) proved too narrow and the inlet was not in equilibrium. The opening of Faro-Olhão Inlet, its stabilisation, and the scouring process related to the evolution of inlet' cross-section towards stability (Figure 48C&D), greatly reduced the flow through the Armona Inlet, resulting in a shift in tidal prism dominance from Armona to Faro-Olhão.

Tidal inlets, particularly when not constrained by jetties, have very high longshore sediment transport trapping capabilities. For an inlet such as Armona, which used to have a tidal prism of 9×10^6 m³, the subsequent flow reduction of about 75% resulted in an over-supply of sediment. Ebb tidal current loss over the shoal allowed waves and flood tidal currents to push the shoal landward. This in turn provided the sediment necessary to enlarge Culatra Island (Figure 48B) and to reduce the width of the Armona Inlet (Figure 48E).

Sediment budget analysis shows that the development of Faro-Olhão Inlet has occurred in three stages:

1. An initial phase of sediment retention (1929-1962), when the inlet started to capture longshore-transported sediment in order to build ebb and flood deltas, and the channel deepened as it evolved to achieve an equilibrium cross-section (Figure 46B);

2. An intermediate stage (1962-1978), during which both deltas accumulated sediments at approximately the same rate and major modifications occurred in both barriers, with significant

accretion at westward located Barreta Island and further inlet scouring;

3. A recent stage (1978-2001), characterised by the evolution of both coastlines in response to the inlet's presence and by drastic intensification of scouring of the inlet gorge (Figure 46C). The strong ebb-tidal currents from this inlet act as an effective barrier to longshore sediment transport, which enhances sand capture updrift of the western jetty, and enhances the retention capacity of the entire submarine strip between the beach and surf zone. The sediment budget analysis also indicated that the inlet reached equilibrium with regard to its cross-section fifty years after its opening. However, it has taken around seventy years to approach equilibrium with the adjacent coastline, and the width of the Armona Inlet has been greatly reduced.

More recently, in the 1990s, two inlets, Ancão (1996, Figure 46) and Fuseta (1999, Figure 47), were relocated. Inlet relocation is a soft coastal management technique that, when applied to migrating inlets, involves the artificial opening of a new tidal inlet along the historic migration path of the inlet. The relocation of the Ancão Inlet was successful and the inlet still maintains its capacity to flush sediments while continuing to migrate. Since its opening the inlet has migrated ~1400m (~90m y⁻¹ until 2010). Conversely, the relocation of Fuseta was not successful because infilling and meandering of the channel occurred after opening. Figure 47 shows a storm that breached Armona Island, ~1000m west of the inlet. The new and old inlets had to be artificially closed, and a new one opened at a more favourable location, that is currently (early 2012) working well.

Within the inner backbarrier system, the main channel (Faro), has been widening and deepening in areas where most of the dredging operations took place, especially since the 1980s. This intensification caused channel

enlargement, eastward migration, and deepening, and loss of saltmarshes. The intensification of dredging increases the hydraulic potential of the channel but can be responsible for silting up secondary channels, altering oxygen supply and nutrient fluxes, affecting economic activities such as wild fisheries (including shellfish) and aquaculture.. Because the Faro Channel is hydrodynamically connected with two inlets of the system, Ancão and Armona inlets, any improvements in its hydrodynamics could have impacts on the neighbouring inlets (i.e. loss of efficiency and infilling).

Conclusions

The opening of tidal inlets and the subsequent readjustment of the tidal prism are responsible for significant changes along adjacent coasts, especially in multi-inlet systems. The process is more evident when jetties are involved in inlet stabilisation, because they disrupt natural inlet migration patterns and impact the overall sediment budget of the coastal cells involved. In most coastal areas affected by engineering activities, it is difficult to collect historical datasets in order to analyse coastline evolution and coastal engineering impacts. Inlet stability is therefore normally inferred from inlet hydraulics, i.e., analyses of cross-sectional area evolution. Although these are important in the study of locational/geometrical stability of an inlet, such analyses should be complemented by tools such as sediment budgets.

The Armona Inlet case highlights the importance that ebb-tidal deltas have in trapping longshore-transported sediment and releasing it again during periods of increased wave activity. Therefore, particularly in multi-inlet system such as the Ria Formosa, the coupling of morphology and hydrodynamics should be extended to all inlets in order to understand the stability of the overall system based on the distribution of the tidal prism through time,

and inlet circulation patterns and their influence on the pathways and magnitude of sediment transport. The long-term equilibrium of sediment storage in the ebb-tidal deltas must be considered when analysing the possible equilibrium of multiple-inlet systems. Thus, a full evaluation of the stability of inlet systems requires a detailed coupling of the backbarrier area, inlet, and ebb-tidal delta, including the effect of waves over the delta and in the adjacent coastal zone, and especially their role in stirring and transporting the sediment.

The management of engineering, environmental, and socioeconomic aspects of complex environments such as the Ria Formosa requires an integrated coastal management program, involving different stakeholders. Advanced knowledge of coastal dynamics and observations of the impacts caused by coastal activities (e.g. harbours, inlets/channel opening and maintenance, coastal defence works) reveal the important coastal indicators that must be included in the decision-making process. In the Ria Formosa there is an urgent need to apply regional sediment management actions, affecting sediment removal transport, and deposition. Common actions include dredging and placement, building structures that divert or trap sediment, bypassing sand from inlets, and erosion protection for banks, shorelines, sea beds, and channel bottoms. Essentially these actions consist of coordinating dredging activities in the coastal zone for the purpose of retaining sand in the littoral system in order to achieve more balanced, natural system processes, and to reduce future project costs associated with channel maintenance. An integrated coastal management program should:

1. Perform detailed sediment budget analysis based on new topo-bathymetric data; in particular, quantify sediment storage at ebb tidal deltas and understand how that sediment can be mobilised by increased wave activity.

TABLE 20	Tasks and costs for the Ria Formosa sediment management plan		
Level	Task description	Period (year)	Costs (2012 euros)
1	Complete topography and hydrographic survey of Ria Formosa system (executed with LIDAR and multibeam echosounder)	12	350 k€
2	Complete hydrographic survey of the all the inlets and inner channels (executed with multibeam echosounder)	6	120 k€
3	Hydrographic surveys of the inlets and main principle channels of water circulation (executed with multibeam echosounder)	3	75 k€
1, 2, 3	Quantify tidal prism evolution and hydrodynamic patterns (ADCP current measurements) for complete spring/neap tidal cycles)	6	15 k€ per survey (all the inlets)

2. Define new indicators based on tidal prism quantification through the inlets, relating changes in tidal prism due to dredging and on the changes in nutrient flux and oxygen supply.

3. Plan dredging of navigable channels to restore system equilibrium conditions, promoting inlet flushing capacity and channel navigability. Priority dredging actions must be planned after major storm events, especially at the Ancão, Armona and Fuseta inlets and adjacent channels;

4. Quantify sediment deficits in the coastal sectors and coastal vulnerability to erosion processes, and define risk management areas associated to inlet hazards;

5. Analyse data and information concerning the ecological, physical and chemical characteristics of the locations to be dredged, to minimise impacts on the surrounding environment (e.g. equipment used, timing and period of dredging);

6. Place sediment from inlet navigability maintenance on those deficit coastal sectors, or use it for beach nourishment, coastal waterfront and/or habitat recovery;

7. Execute long-term monitoring of sediment bypassing processes prior to the opening of a new inlet;

Table 20 presents three levels for planning and execution of a sediment management coastal plan in the Ria Formosa. Such a plan will able to establish priority actions regarding dredging operation and reinforcement of coastal sectors. A "build with nature" strategy should be followed, i.e. sand nourishment, and the recovery of coastal environments (e.g. dune systems, tidal flats and salt marshes), should be part of the strategy to address erosion.

This approach avoids the hard engineering structures (e.g. jetties) that will inevitably divert coastal sediments and cause erosion problems.

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CASE STUDY 2: OFFSHORE AQUACULTURE IN ARMONA[4]

The European Union COEXIST project (www.coexistproject.eu/) uses several case studies to test different methodologies for harmonisation of fisheries, aquaculture, and other activities in the European marine domain. One of these studies includes the Pilot Area of Aquaculture Production of Armona (APPAA)

FIGURE 49 APPAA Pilot Aquaculture Production Area, off Armona, Ria Formosa. The inner rectangles drawn within leases are the actual cultivation area
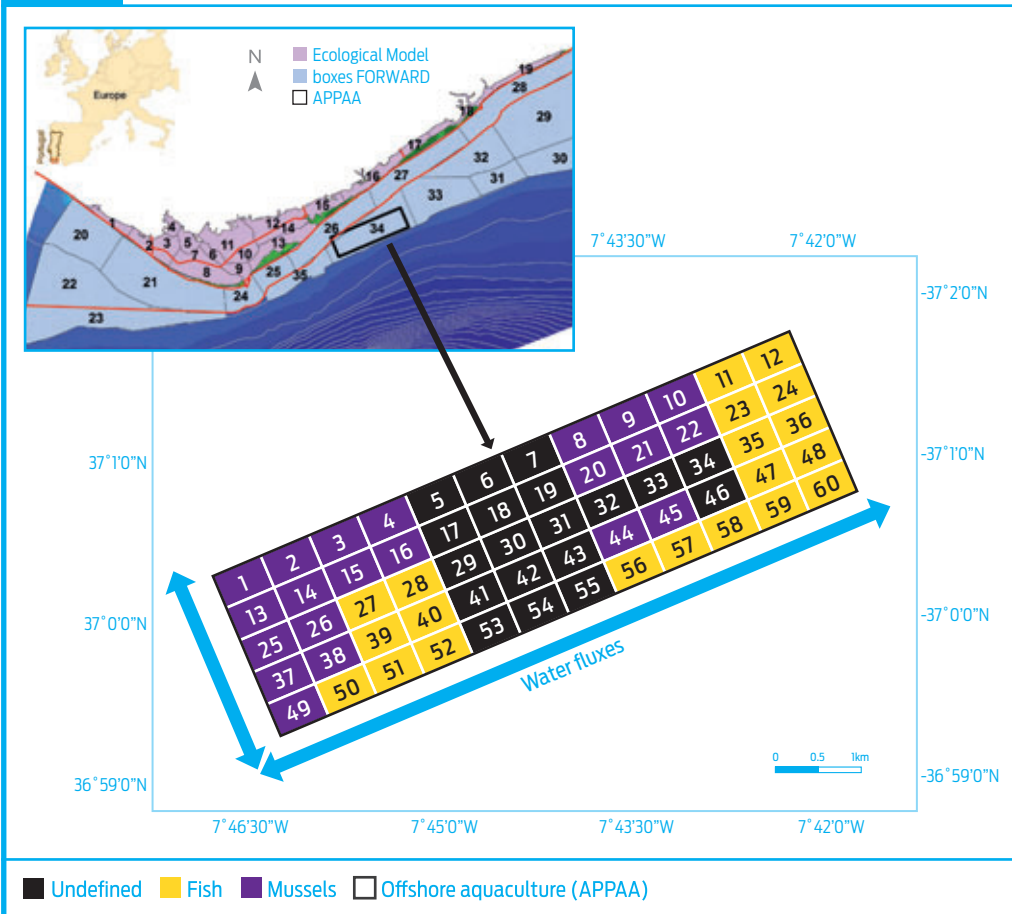
located offshore (on the 30 m bathymetric contour) of the large inlet of Olhão, Ria Formosa, southeast Portugal.

The APPAA (Figure 49) is a 15 km^2 area established by the Portuguese government for integrated multi-trophic aquaculture (IMTA). The aquaculture park contains 60 leases, each with a cultivation area of 80 000 m^2; a maximum of 70% of the leases will be used for finfish culture, and a minimum of 30% for bivalves. The EcoWin2000 ecological model was applied within the COEXIST project to simulate the production, economics, and environmental effects of the APPAA. Some results are presented below for monoculture of Mediterranean mussel (*Mytilus galloprovincialis*) and for integrated multi-trophic aquaculture with gilthead bream, *Sparus aurata*.

Mussel monoculture

Production of mussels in monoculture was simulated for 21 leases, based on the licences granted by the regulator (Figure 49). The cultivation was simulated for a period of four years, using current velocities provided by the hydrodynamic model, and food drivers (temperature,

FIGURE 50 Mussel production at different culture densities in mono or multitrophic culture with fish, example of four leases (locations in Figure 49).
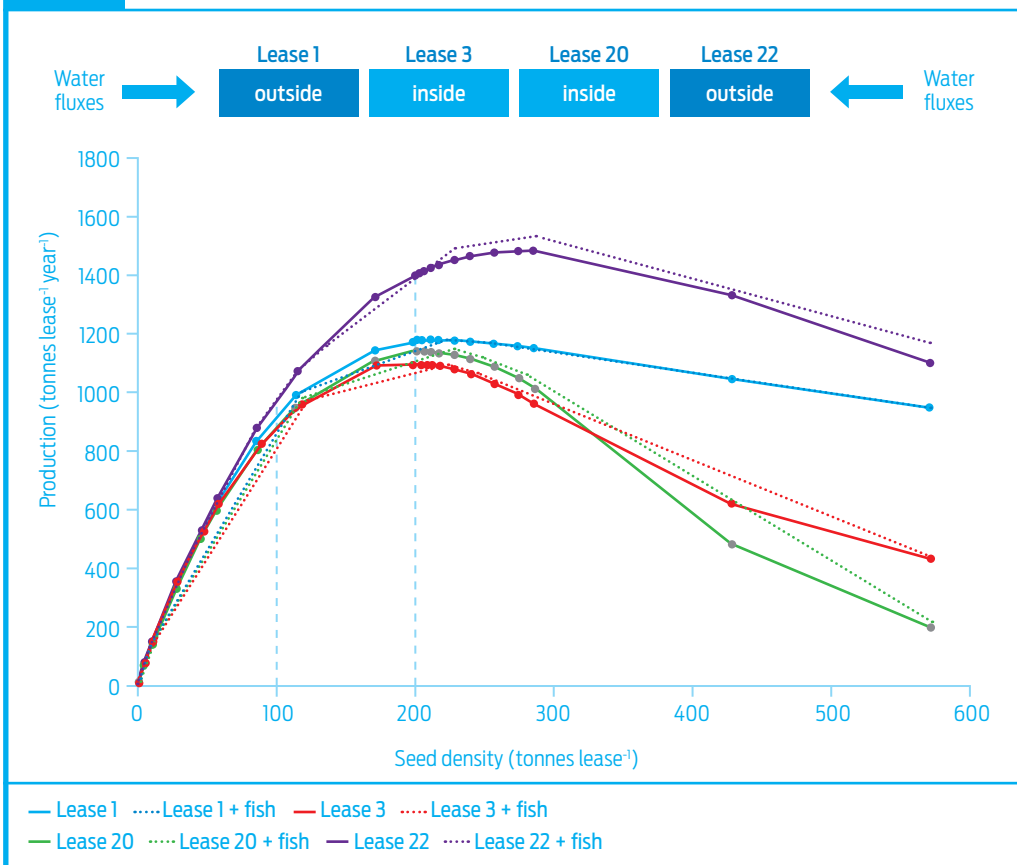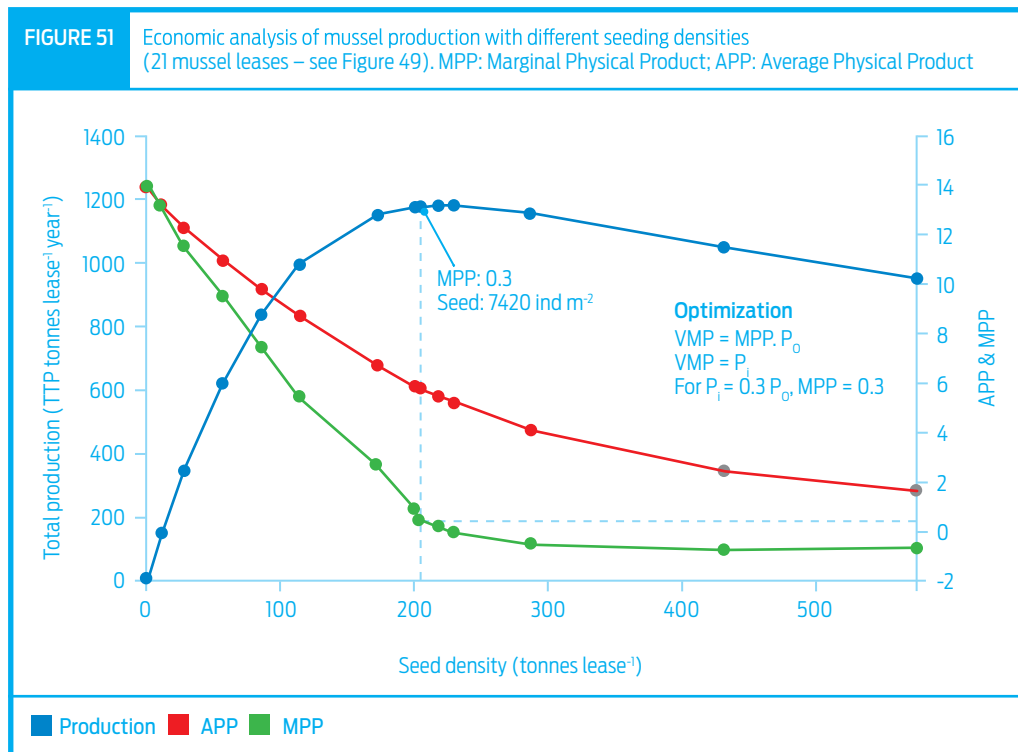
salinity, chlorophyll a, and organic detritus) taken from the FORWARD ecosystem model. Figure 50 shows the results at four leases, for different seeding densities.

The maximum production at the outer edge of the APPAA peaks at 1500 tonnes per lease (260 tonnes per hectare), while the inner leases produce no more than 1100 tonnes (200 tonnes per hectare). At the boundaries of the model, the southeastern edge (lease 22) receives a better food supply, which accounts for the higher yields. Food depletion affects harvest when the seeding density exceeds 100 tonnes (17.5 tonnes per hectare); at densities above 200 tonnes (35 tonnes per hectare), yields are below the maximum production at the inner leases, although they are still increasing slightly at the outer edges of the aquaculture park.

Figure 51 shows a marginal analysis to determine optimal profit for the farms. In lease 1, for a marginal physical product (MPP) of 0.3 (seed cost P_i = 0.36 €/kg and harvest price P_o = 1.08 €/kg), the seed density for a maximum profit is 37.1 tonnes per hectare.

This value is slightly lower that the seed density for maximum revenue. The optimal seed density depends on the location of the lease within the APPAA – in the example leases in Figure 51, this varies between 7000 and 9600 individuals per m^2 (i.e. 35-48 tonnes per hectare).

For an optimal seeding density of 37.1 tonnes per hectare, the simulated total yield of mussel monoculture is 36 000 tonnes per year, corresponding to an annual gross income of 38.8 million euros.

FIGURE 51 Economic analysis of mussel production with different seeding densities (21 mussel leases – see Figure 49). MPP: Marginal Physical Product; APP: Average Physical Product

Integrated Multi-Trophic Aquaculture (IMTA)

The ecological model was run for a three year growth simulation with mussels at different densities, stocked in twenty one leases, together with twenty leases for gilthead bream culture (Figure 52).

The environmental forcing used to drive the model is identical to the monoculture scenario, and the model was run with five different mussel seed densities: 2, 20, 40, 50 and 100 t ha^{-1} for the twenty finfish leases. The release of particulate organic matter from finfish culture was simulated as a constant input to the environment using a density of 400 fish per m^2, which corresponds to 4% occupancy of a lease.

Figure 52 shows that the mussel production is lower in the inner leases (3 and 20) and higher in outer ones (1 and 22), both with and without finfish, due to reduced food availability inside the APPAA. Mussel production is consistently higher in lease 22, due to an extra subsidy of organic matter from finfish in adjacent leases, together with more favourable boundary conditions. At the maximum seeding density of 100 tonnes per hectare (Figure 52), this increase in mussel production reaches 68 tonnes per year in lease 22, six percent more than the lease yield in monoculture. It would thus appear that IMTA with finfish in adjacent leases favours the growth of mussels, which re-use organic matter from finfish culture as a food source; however, the percentage increase per lease is relatively small.

FIGURE 52 Production in mussel leases at different seeding densities, in IMTA with finfish (20 leases shown in yellow)
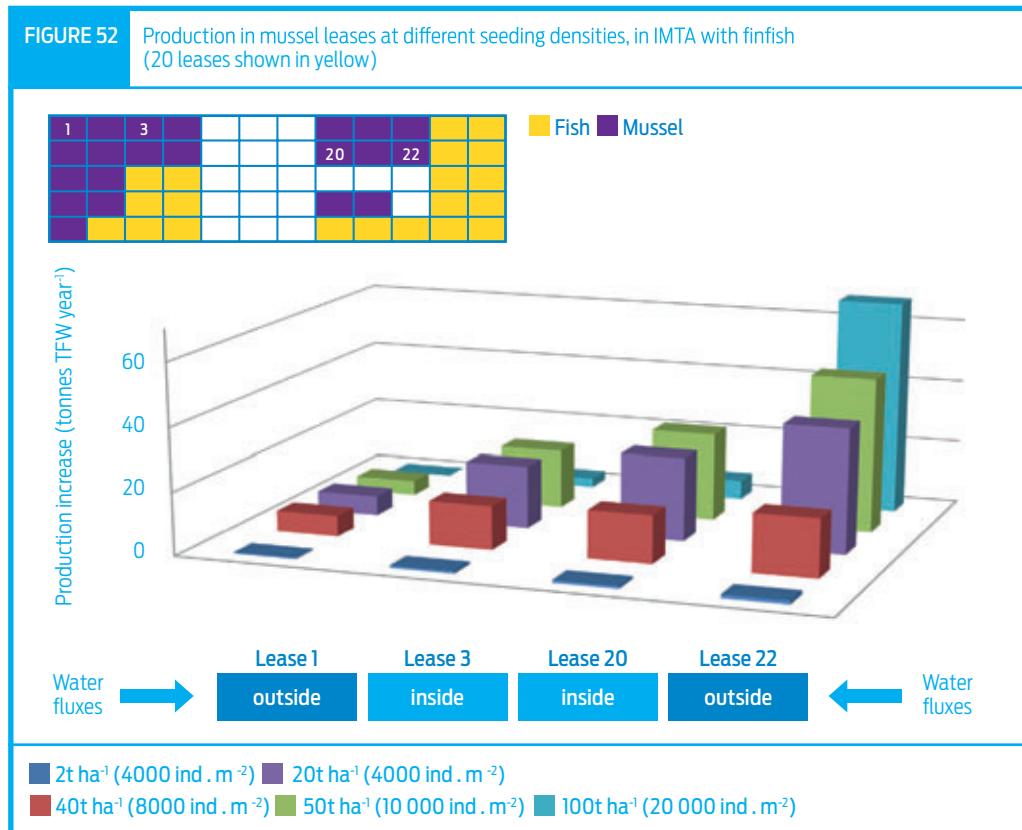
Ecosystem goods and services in IMTA

Table 21 shows the annual mass balance of ecosystem goods and services provided by the mussels in the APPAA cultivated in IMTA. The application of the Ecowin2000 model indicates that there are environmental benefits of co-cultivation through the reuse of nitrogen and phosphorus from organic detritus, both for mussel production, and in mitigating environmental impacts of finfish monoculture.

The increase in the total production under the IMTA scenario is 53 tonnes per year, valued at about 59 000 euros. This is not a significant change from monoculture, but the mussels additionally supply an important environmental service. The total removal of particulate organic matter (POM) equates to almost 6500 tonnes of carbon and slightly over 1000 tonnes of nitrogen per year, for a mussel seeding density of 2 tonnes per hectare at the 21 leases. The model indicates that nitrogen removal corresponds to just over 10% of live weight production.

The nitrogen drawdown by mussels corresponds to a population equivalent (PEQ) of about 240 000 inhabitants per year, i.e. an annual positive externality in excess of 7 million euros per year (Table 21). In this case, this is not a substitution cost of land-based removal, but an even more

TABLE 21	Ecosystem services provided by bivalves in the APPAA
Item	Value
Goods	
Mussel production	
Harvested biomass (t y^{-1})	9512
Value (thousands of euros)	10 273
Services	
Carbon (gross)	
Detrital POM removal (t C y^{-1})	5157
Phytoplankton removal (t C y^{-1})	1318
Total POM removal (t C y^{-1})	6476
Nitrogen (net)	
Detrital POM removal (t N y^{-1})	802
Phytoplankton removal (t N y^{-1})	205
Total POM removal (t N y^{-1})	1007
Ecosystem services	
Population equivalents (PEQ)[8]	243 030
Externality value* (thousands of euros)	7290
Total goods and services (thousands of euros)	17 563

7: Only calculated for detritus, assumed to originate from finfish culture

8: 1 Population-Equivalent (PEQ) : 30 € year^{-1}

FIGURE 53 Food availability in the APPAA with different culture combinations (mussel density: 2 t ha⁻¹)
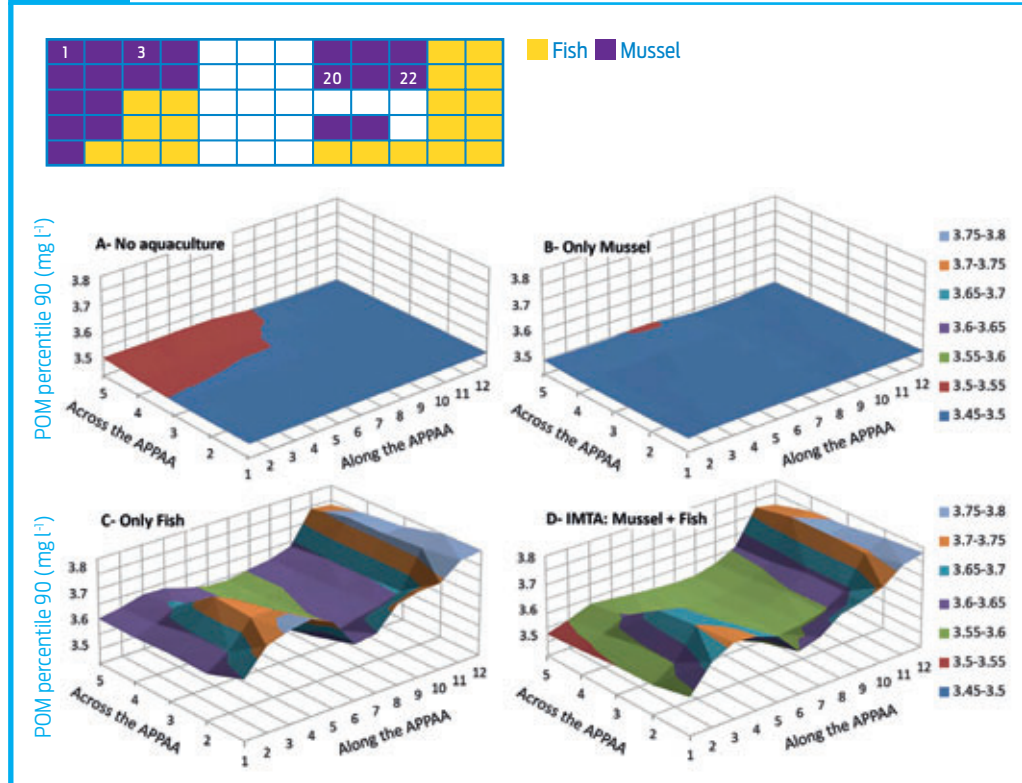
valuable service – surplus organic material from finfish farms, introduced both as unused food and faecal waste, corresponds in practice to non-point source pollution, and leads to well identified acute local impacts. It is notoriously difficult to reduce at source or remediate post-facto. IMTA is a practical alternative, and in periods of reduced algal food supply, may significantly enhance shellfish production.

The effect of different culture combinations (monoculture and IMTA) on the APPAA as a whole can be seen in Figure 53, which uses the percentile 90 for chlorophyll as a proxy for food availability. The increased food supply at the eastern (right-hand) boundary is clearly visible, particularly in IMTA.

Different scenarios can be tested by means of the EcoWin2000 model, through alternate combinations of species, densities and locations within the APPAA. These provide information on production, environmental services and on socio-economic and environmental sustainability of aquaculture, helping to inform management decisions.

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CASE STUDY 3: DISEASE: LESSONS FROM SCOTLAND, NORWAY AND CHILE[9]

Any production of animals for human consumption is influenced by disease as a risk, as a limiting factor, and as a factor that may reduce product quality and safety. Rearing large numbers of animals of the same species in limited space favors establishment and proliferation of pathogens, i.e., viruses, bacteria and parasites capable of exploiting the reared animals as hosts. However, this is not a direct relationship, as there are several factors influencing the balance. The risk and impact of pathogens may be either increased or reduced by a wide set of biological modulations and other management practices, emphasizing the importance of understanding the dynamic ecology of the host-parasite-relationships.

In aquatic environments, diseases can be spread from wild to farmed animals and vice-versa. Due to the artificially high host density in aquaculture there is a risk for proliferation and enhancement of virulence of the pathogens in farmed populations, thereby in turn increasing the pressure on wild animals. Water currents provide good vectors for dissemination of many pathogens, and many parasites display

Figure 54. Salmon lice on an infected fish.

impressive adaptations to this environment. In this case study, we focus on some key aspects of diseases in aquaculture: susceptibility of hosts, spreading of pathogens, management regimes, fallowing, and the all-in-all-out principle. Annual production of Atlantic salmon in Norway is nearing one million tonnes. Scottish production is at 160 000 tonnes and Chile was producing around 280 000 tonnes per year before the increase in sea lice (*Caligulus*) at the end of 2006, followed by infectious salmon anaemia in 2007. The understanding of disease, impacts, and measures taken by environmental managers and the industry is an important lesson to avoid repeating past mistakes.

Susceptibility of hosts

The susceptibility of any individual host to a pathogen is influenced by the complex inter-relationship between the genetics of the host and pathogen, and the environment within which the host is living.

Different stocks of wild and cultured aquatic animals can vary greatly in their inherent

resistance to disease. For instance, Baltic and North Atlantic stocks of Atlantic salmon vary greatly in their relative susceptibility to the monogean parasite *Gyrodactylus salaris*. The introduction of Baltic strains of Atlantic salmon carrying the pathogen into Norway likely afforded the opportunity for *G. salaris* to spread into wild Atlantic salmon there, with catastrophic consequences for stocks in a number of rivers.

Similarly, it is now well established that different families of Atlantic salmon display marked differences in their susceptibility to the viral pathogen *Infectious Necrosis Virus*, with this variation largely explained by relatively small differences in host genetics.

Variation in disease susceptibility is often a factor affecting species selection. For instance, one of the reasons Atlantic salmon, as opposed to native *Onchorynchus* spp., are farmed in sea cages off the coast of Western Canada is that they are less susceptible to Bacterial Kidney Disease, endemic in the wild stocks of salmon there. As well as variation in host genetics affecting disease susceptibility, different strains of pathogens can also show marked differences in virulence. For example, the bacterial pathogen *Yersinia ruckeri* causes the disease Enteric Redmouth Disease in rainbow trout and other salmonid species.

However, only some of the serotypes cause severe disease in rainbow trout, with other subtypes particularly affecting Atlantic salmon. Bacteria and viruses also have a propensity to undergo genetic recombination, including, particularly in the case of bacteria, an ability to acquire genetic elements that confer increased virulence, resistance to antibiotics etc. This affords a mechanism by which they can rapidly evolve to cause enhanced levels of disease in previously susceptible species, previously resistant species or strains of host, as well as

circumvent control strategies (chemotherapy, immunoprophylaxis etc.)

As well as being influenced by genetic variation at the host and/or pathogen level, susceptibility to disease is affected by the environment. For instance, it is well established that many diseases are more prevalent at particular times of year than others. Diseases are often temperature-dependent, with diseases that are more prevalent at higher temperatures (e.g. *Lactococcus garvieae* affecting rainbow trout, francisellosis in cod) and others that are typically only seen when temperatures drop below a certain threshold (e.g. koi herpes virus in *Cyprinus carpio* and ornamental variants and francisellosis in tilapia). Often this is the result of interplay between the ability of any particular pathogen to survive and replicate at a particular temperature range and the relative ability of the host to mount an effective immune response that is, itself, also typically temperature dependent.

Related to this, age, background immune status and overall condition of the host are crucial factors that will affect host susceptibility. Typically, stress increases the susceptibility of fish to disease, with release of cortisol resulting in immune suppression. Fry that have not attained full immunocompetence may also be much more susceptible, with many examples of diseases, such as IPN in rainbow trout that typically affect mainly young animals.

Changes in physiological status, e.g. transfer of Atlantic salmon smolts from fresh to seawater can also result in increased susceptibility to diseases such as IPN. Fish that have already been exposed to disease agents may also be protected against subsequent exposure. Another obvious factor that will affect the ability of aquacultured animals to resist pathogens is whether they have been treated. This could include both immunoprophylaxis, where fish have been immunized by vaccination against

particular diseases or chemotherapy, where fish are treated with chemicals (including here antibiotics).
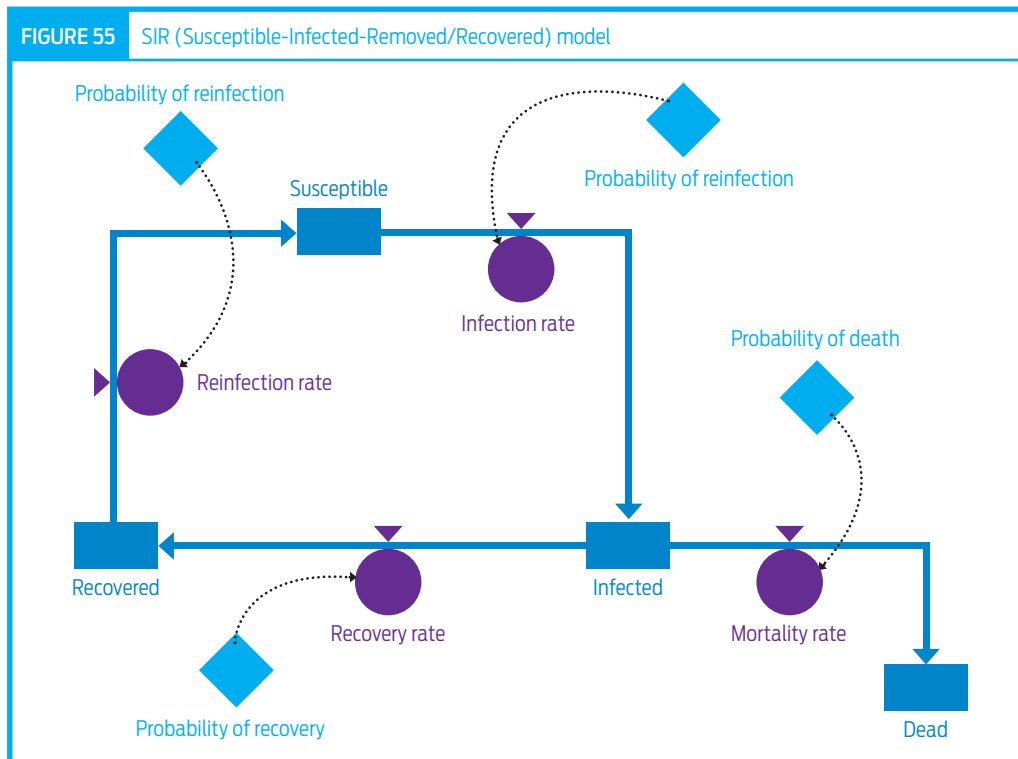
Spreading of pathogens

Pathogens may be spread by wild organisms, escapees from aquaculture, transport of cultured organisms, transport of equipment or people, ballast water from ships or water currents. Although disease is a major limiting factor in aquaculture, disease modeling is presently under-utilized. Two common approaches are compartment-based models and network-based models.

Compartment-based models assume that individuals go through a series of states from susceptible to infected and potentially back – or to resistant (Figure 55). Among important

information that can be derived is a maximum (susceptible) host carrying capacity for which a pathogen cannot persist, often referred to as the critical threshold NT. In aquaculture, the ratio NT/N, where N is the total population, may be manipulated by enhancing resistance through selective breeding, improved biosecurity, or immunoprophylaxis; improved management has the potential to increase the maximum density at which a species can be reared safely with respect to the risk of pathogen proliferation.

Network based models take into account the contacts between populations and individuals that actually do take place, for instance including data on movements of populations, water currents or vectors of transfer. Much useful information can be obtained merely by examining the network properties *per se*, without parameterising for a particular disease.

FIGURE 55   SIR (Susceptible-Infected-Removed/Recovered) model

Hydrodynamic models have been applied to monitor spreading of pathogens in coastal and fjord environments. Such models have been applied particularly to salmon lice. By elucidating the potential of salmon lice larvae to spread over long distances, the models have provided useful input for improved management regimes and legislation, emphasizing the need for synchronous antiparasitic measures in large management zones.

Biosecurity

The application of biosecurity in aquaculture is a shared responsibility. Individuals, governmental and local authorities, and aquaculture production businesses play different roles in implementation. Biosecurity can include practical and legislative control measures, adequate diagnostic and detection methods for infectious diseases, disinfection and pathogen eradication methods, reliable high quality sources of stock, and best management practices.

The Finfish Biosecurity Measures Plan by CEFAS, U.K. identifies several steps in implementing biosecurity at farm level. Many of the steps are equally relevant at different levels of governance.

1. Appointing a biosecurity manager
2. Appointing veterinary health contacts, if possible including fish disease experts
3. Staff training in fish health management and disease recognition for relevant species
4. Identifying the risks of contracting and spreading disease through movements
5. Identifying risks of contracting and spreading disease as a result of site procedures
6. Measures to limit risk
7. Monitoring of the plan
8. Contingency planning

Figure 56. View of a typical Norwegian fishfarm. Each cage holds about one thousand tonnes of fish. Appropriate site selection, biosecurity measures and environmental monitoring ensure the fish remain free of disease and are grown to the highest standards of sustainability.

Documentation and clearly defined ways of reporting are key measures in the plan. Furthermore the plan emphasizes the need for competence, both with respect to veterinary health contacts and the general staff of the farm. Monitoring is necessary, as biosecurity and fish health is an endless war with victories and defeats. Furthermore, measures for risk limitation and the need for contingency planning in order to limit disease outbreaks are necessary.

Biosecurity aims more at prophylaxis, i.e. prevention of disease rather than treatment. Although many diseases may be treated, the chemicals used are often associated with negative environmental effects, reduced animal welfare, and high costs. Therefore, emphasis should be placed on prevention by measures such as the biosecurity measures listed above, and, if possible, immunoprophylaxis. Without vaccines and biosecurity measures, there would probably not have been a salmonid aquaculture industry. It is likely that other sectors of the aquaculture industry will implement similar measures.

Fallowing and the all-in—all-out principle

Mandatory fallowing of aquaculture sites has been implemented in parts of the aquaculture industry. The principle is based on removal of hosts, thereby removing the possibility for pathogens to proliferate at the expense of hosts. In the case of obligate pathogens, this effectively blocks pathogen proliferation. However, this is not the case for facultative pathogens, which may survive in the environment, independent of hosts. The effect of fallowing is also limited if hosts are present in the environment surrounding the aquaculture site. This is not the case in the part of industrial aquaculture where fallowing is most common, land-based hatcheries. Disinfection and drying of the hatchery is routinely done after a production cycle. This is in principle fallowing, and re-sets the abundance of pathogens to zero or near-zero before the next cycle is started.

In cage farms, the system cannot be manipulated to this extreme. In the case of salmon lice in Northern Europe, wild salmonids provide a possibility for the natural reservoir of parasites to persist. However, in Norway and Scotland, the number of farmed salmonids (Atlantic salmon and rainbow trout) far exceeds the number of wild salmonids (Atlantic salmon and sea trout), thereby the quantitative reduction of hosts during fallowing implies that the numbers of wild salmon lice, and other parasites are reduced.

As pathogens are spread by currents and vectors, fallowing and other hygiene measures of individual farms may not be enough. In particular, salmon lice are well adapted through evolution to the hydrographic conditions of fjords, with a fast moving freshwater and brackish water layer on top of the seawater. Moving around in this layer, the salmon lice larvae can be transported, infecting wild and cultured salmon in large areas. For this reason, there is presently a tendency to develop the legislation and management procedures towards mandatory synchronized antiparasitic treatments, slaughtering of fish, followed by fallowing and restocking in all farms in management zones comprising several municipalities, or even counties.

After the period of fallowing, aquaculture sites are restocked with a new generation of fish. In salmon farming, this is done by an all-in-all-out principle. After new smolts have arrived, no new arrivals are permitted until the end of the production cycle, when fish can be slaughtered and a new sequence of fallowing followed by yet another restocking. The all-in-all-out principle blocks transfer of pathogens between the production cycles, as no contact between generations is allowed. Furthermore, during the period of fallowing, the populations of pathogens are left without hosts, or only with the wild host populations, thereby reducing pathogen numbers. The principles have not

been enforced to the same degree in farming of species other than salmonids. For instance, in cod farming, generations have generally been mixed. Furthermore, the use of wrasse as cleaner fish of salmon lice introduces several problems, as the wrasse species have different generation times to the salmonids. Transport of wrasse between different regions also constitutes a risk for disease transfer. Increased industrialization of the industry, including larger management zones, and improved health control that includes aquaculture of wrasse, may increase the biosecurity.

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CASE STUDY 4: TAYLOR SHELLFISH: GROWING A BUSINESS FOR THE COMMUNITY

After trying his hand at ranching in Arizona with U.S. western hero, Wyatt Earp, J.Y. Waldrip moved to western Washington State in the 1880s where he fell in love with oyster farming in Puget Sound. J.Y. Waldrip created a legacy now run by the family's fourth and fifth generations that has carried on for more than one hundred years, and has become the largest producer of farmed bivalve shellfish in the United States. This case study provides an accounting of the Taylor Shellfish Farms success story.

The fourth Taylor family generation, Bill and Paul Taylor and their brother-in-law Jeff Pearson, like J.Y. are modern day shellfish farming pioneers. The Taylor family has commercialized shellfish

Figure 57. J. Y. Waldrip building dikes for native oyster culture.

production and built the markets for high quality shellfish on a scale previously unrealized in the U.S. shellfish farming industry. Over the past three decades they have done more to modernize and grow the U.S. Pacific Northwest shellfish industry than any other shellfish farming family in the country. At present, Taylor Shellfish Farms employ approximately 480 people on 11 000 acres (4450 ha) of tidelands and in processing facilities in the Puget Sound region, the Washington coast, British Columbia, and Fiji.

Hatchery seed production fundamental to success

Prior to the 1970's the U.S. Pacific Northwest shellfish growers relied on Pacific oyster (*Crassostrea gigas*) seed imports from Japan, or collected seed from specific bays where Pacific oysters had naturalized. Manila clams (*Ruditapes philippinarum*) were the other main commercial species and growers relied

on natural recruitment. Since Pacific oyster and Manila clam are introduced species, recruitment was sporadic and unreliable.

In the early 1980s, Bill and Paul Taylor opted to expand the business their father and uncle had been running by taking back oyster and clam land leased out to other companies and boosting production. They soon recognized they needed a secure source of seed. This became painfully evident following a massive clam mortality event in 1980. They forged a working relationship with the Whiskey Creek shellfish hatchery on the Oregon coast for both clam and oyster seed.

In 1989 the company built their first hatchery on Dabob Bay, Washington, to provide a stable supply of oyster and clam seed. It also allowed the company to diversify the species of shellfish farmed and the type of seed produced. Diversification provided stability.

Growing multiple species buffered the company against demand and price dips on any one species. Focusing on the most profitable species improved the profitability and was instrumental in funding research and development to make further advances in production. After mastering hatchery production of oyster and clam seed, the company expanded the operation to include production of Mediterranean mussel and geoduck clam seed.

While the Dabob Bay hatchery was built to supply seed for Taylor's company, they have become a key supplier of clam, oyster, mussel and geoduck seed to the entire North American west coast shellfish industry. The company has a hatchery/nursery team that meets regularly to schedule production and plan infrastructure development to fulfill internal and external seed needs. These efforts have led to the installation of a large floating upwell nursery (FLUPSY) in Oakland Bay in Shelton, Washington, a hatchery/nursery facility in Kona, Hawaii, a remote FLUPSY in Desolation Sound, British Columbia and acquisition of a large shellfish nursery operation in Humboldt Bay, California. These facilities are perpetually expanding and changing as technology for culturing algae, larvae and seed evolves and demand continues to grow.

Taylor's hatchery capabilities were very helpful during the 1980s when markets shifted toward single oysters for the oyster bar trade, having been focused on shucked oysters from the mid-1920s through the 1970s. The hatchery, along with expanded nursery capacity, allowed the company to follow market demand and also allowed production of a diversity of oyster species including *Crassostrea gigas*, *C. virginica*, *C, sikamea*, *Ostrea lurida* and *O. edulis*, as well as production of sterile triploid oysters for improved yield and summer marketability. In

coordination with the Molluscan Broodstock Program at the Hatfield Marine Science Center in Oregon and others, Taylor Shellfish has also been actively involved in the development of breeding programs for improved stocks of oysters and clams. This will be an area of increased focus in the years ahead as the company recognizes the benefits of this research.

In the mid-1990's Taylor's realized that hatchery production in the Pacific Northwest was limited by the lack of sunlight in the winter to grow algae necessary to feed their animals, and cold water that required heating to increase seed metabolism to feed. This resulted in early summer seed shortages and late summer surplus. In 1995 they opened another hatchery facility in a warmer, sunnier climate, Kona, Hawaii, which has led to dramatic production improvements with ripple effects throughout the industry. Having seed available in the spring and early summer allowed farmers to take advantage of the summer growing season, cutting up to a year off the time to market. Supply from the remote seed production facility works because millions of animals can be transported cost effectively when they are in the 0.25 mm to 15 mm size range. Taylor's Kona facility has revolutionized U.S. west coast shellfish production.

Hatcheries have been fundamental to Taylor's success, but they are also incredibly expensive and frustratingly fickle. Each site is unique. Water chemistry varies as does the flora and fauna that get pumped into the facility. Despite attention to these details by two PhD level scientists and multiple technicians, production can fluctuate wildly for often unexplained reasons. Recently, Taylor's and others realized that ocean acidification is impacting oyster seed production, which led to a new focus on monitoring and adaptation strategy

development. The company maintains a high health program at the hatchery and contracts with a pathologist to certify the health of their stocks. A clean health history is key to maintaining production and the ability to ship seed across national and international borders.

Tideland ownership instrumental to Taylor's success

In contrast to most of the coastal United States where land for aquaculture must be leased from the government, Washington State allows ownership of the tidelands that are farmed.

In the 1800s there was a wild fishery for *O. lurida*, the oyster native to the U.S. Pacific Northwest. However, as with many fisheries, the tragedy of the commons resulted in depletion of oyster resources. Some of the earliest laws passed by Washington's legislature, shortly after becoming a state, were oyster-related in an attempt to recover the resource. These laws preserved productive oyster beds as "oyster reserves" and offered barren tidelands for sale for the purpose of growing the native oyster. Any use other than growing oysters resulted in ownership reverting back to the state. The laws later changed to allow culture of other shellfish species and, for a period of time, the purchase of the reversionary rights.

Ownership is a fundamental reason why Washington leads the U.S. in farmed shellfish production today. Banks are reluctant to loan money for aquaculture, even more so when the land on which the business is to be based is leased with no assurance the lease will be renewed. Ownership provided Taylor's and other shellfish growers with an asset against which they could borrow money for the purchase of seed or resources to expand their businesses. It has also made shellfish growers'

ardent defenders of water quality and given them a more effective voice in that battle. For example, they have successfully used trespass laws to force pollution abatement when faecal bacteria originating from failing onsite sewage systems or agricultural runoff has contaminated their shellfish beds and impacted their farms. Taylors and the growers association have staff dedicated to working with local, state and federal governments to ensure there are adequate septic and stormwater laws and regulations to protect their farms and that they are being enforced.

Public affairs efforts pave the road ahead

During the 1980s, Taylor Shellfish grew rapidly but did not always pay adequate attention to regulatory requirements. In 1993 a public affairs team was established that is dedicated to compliance. Bill Dewey has served as public affairs manager since that time. The public affairs department, with a staff of five, ensures the company is complying with regulations, and does ongoing licensing of operations and permitting for new facilities.

The team proactively engages in public policy debates on local, state, federal and international policy, laws and regulations that impact the company and the broader industry. Taylor Shellfish also actively supports political candidates who they believe will represent them on issues of importance to the company and industry. Two of the public affairs staff are dedicated to outreach and education. The team seeks out print and television media opportunities. In addition to their full time public affairs staff, Taylor Shellfish budgets over $1 million annually for attorneys and consultants to assist with permits and public policy matters as well as media and product promotion efforts. While the public affairs efforts benefit the company, most are done in coordination with and in an effort to benefit the entire industry.

Not afraid to make mistakes

The Taylor family eats, sleeps, and breathes shellfish in an effort to evolve how they farm and process shellfish. Profits are cycled back into the company to increase and improve production and Taylor's continually experiments with new techniques and technologies. For every success there are multiple failures. Bill Dewey says he measures the success of shellfish companies he visits by the size of their bone yard and Taylor's have the biggest he has seen yet. They are not afraid to try and fail and it is not unusual to do so on a large scale, with successes outnumbering failures. They compensate their employees well and reward good performance which ensures they attract and keep a talented staff.

Taking advantage of growth opportunities

Many shellfish farms in the U.S. Pacific Northwest are multigenerational. In the United States it takes careful planning and a lot of resources to successfully pass a business from one generation to the next due to the substantial estate taxes levied by the federal government. The estate tax issue coupled with the fact that shellfish farming is hard work that subsequent generations may not be interested in doing results in shellfish companies periodically coming up for sale. Taylor's, now recognized as a qualified buyer, is routinely approached with farm purchase opportunities with assurances that the sellers are passing the company to someone who knows how to successfully operate a shellfish farm. The U.S. estate tax laws also apply to the Taylor family, but they are determined to successfully pass the family business to the fifth generation, who already occupy management positions in the company. The family is actively involved in estate planning with attorneys and consultants to ensure a seamless transition.

As the company struggles to get permits for new farms in Washington State (15 years and counting with over $1 million in costs for study, appeal, etc. for a new 1 hectare mussel farm), they have taken advantage of an abundance of existing farms for sale in British Columbia, Canada. Over the past eight years they've invested ~$15 million USD purchasing Canadian farms. Their B.C. holdings now include about 100 hectares of farms and a processing facility, which collectively employ about 100 people.

In the 1990s, Taylor's launched into black pearl culture in Fiji. Today, with two farm locations J. Hunter Pearls is Fiji's largest and most prestigious pearl producer, and still very much part of the Taylor Family.

In the late 1990's the Taylors recognized the potential of farming the high value giant geoduck clam. These clams (Figure 58), which take an average of 6 years to reach the 1 kilogram market size, had been harvested subtidally by divers since the early 1970s. In 2000, the Quilcene, Washington hatchery was expanded to produce more geoduck seed. With this expansion and considerable research and development on nursery and farming methodology Taylors have become the leading producer of farmed geoduck clams in the world. When the company started farming geoduck they were selling for $15-20 USD/kg and today they sell for $65/kg.

In 1997, after years of selling product into Asia, Taylor's bought a wholesale distribution company in Hong Kong so they could better control the marketing and sales of their perishable products. This has had a dramatic effect on how the Chinese view and purchase shellfish and has positively impacted the Asian market for shellfish. Today, Taylor's sells directly to restaurants and hotels, and manages seafood retail counters in Hong Kong and south China, along with one retail store, branded as Taylor Finefoods, Ltd.

Figure 58. Six year old geoduck clam with siphon extended.

The market shift from shucked to single oysters in the 1980s not only required major changes to the seed production infrastructure as described above, it also required new processing facilities.

In 2006 Taylor completed a new twenty thousand square foot state-of-the-art processing plant which is dedicated entirely to single specialty oysters. This includes automated sizing and grading equipment, a liquid nitrogen freezing line to accommodate the emerging market for "top off" frozen half shell oysters, and an 8000 square foot (750 m^2) storage freezer with the capacity to hold 850 pallets of product.

Management

Executive management of Taylor Shellfish Farms consists of fourth Generation Bill (CEO) and his brother Paul Taylor (COO) and brother-in-law, Jeff Pearson (CFO). Bill oversees processing, marketing and public policy. Paul oversees farm production and maintenance. Jeff Pearson joined the company in 1990. Jeff uses his finance background to oversee accounting and sales. This family leadership team has been very effective at growing the company.

Below the family executive management team are a half dozen Division Managers overseeing

Figure 59. Oysters on the half-shell and quick-frozen for export.

intertidal (exposed at low tide) farms, subtidal (deep water suspended culture) farms, processing, public affairs and geoduck clam culture. Below the Division Managers are numerous farm managers (Area Managers). In recent years Taylor Shellfish has shifted from managing farming operations by species to having managers oversee individual farms or groups of farms. Each farm has its own budget. Farm managers participate in budget development and are rewarded based on performance. Managers are given latitude and encouraged to farm the most profitable crops and to experiment with new technology and methods to improve efficiency, quality and profitability.

Superworkers become supervisors

In the U.S. Pacific Northwest there aren't schools or programs that provide training in shellfish farming. Taylor's and other growers typically single out workers who demonstrate interest and willingness to learn and improve. Successful shellfish culture involves a sixth sense that is rare among average workers. Managers are those who take an interest in growth rates, survival, predation and other details critical to succeed growing shellfish. They observe and control predators, maintain culture and farming equipment, measure growth, inventory crops, monitor survival and so on. Most of Taylor's farms are on the beach

TAYLOR SHELLFISH FARMS TIMELINE

Year	Event
1980s	fourth generation returned from college to work in family business
1980	began buying "eyed larvae" for artificial oyster setting
1980	began seeding clam ground after big mortality event
1981–83	took back leased shellfish ground, build new shucking plant, sales office and ice room.
1986–87	purchased Ellison Oyster Company
1987–88	purchased the Dosewallips farms on Hood canal
1989	built the Quilcene Hatchery on Dabob bay
1989	tribes sued to determine treaty rights to shellfish ground.
1991	purchased the Samish Farm (Rock Point) from the Steele Family
1994	tribal treaty rights litigation went to court
1994–95	Treaty rights cloud hangs over business as battle ensues in court
1995	Judge Rafeedie treaty rights implementation order
1995	began search for other hatchery sites with warm water and more sunshine
1996	founded Kona, Hawaii site and partnered with Lee Hanson on new hatchery project
1996	first commercial planting of geoduck
1996	wet storage built for clams, mussels and oysters
1997	Hong Kong distribution center and retail store
1998	purchased 6000 acres in Willapa Bay
1999	founded Fiji Black Pearl farm
2000	Quilcene Dabob Bay hatchery expansion for geoduck production
2002	purchased the Okeover Inlet British Columbia mussel farm
2006	finished new single oyster processing plant with freezer line
2007	purchased Fanny Bay Oyster Company, Baynes Sound British Columbia
2007	signed the $33 million treaty rights settlement
2008	finished Flupsy expansion in Oakland bay
2008	Hawaii hatchery expansion finished
2009	purchased Kuiper Mariculture
2010	launched planning/permitting for major Flupsy expansion at Kuiper Mariculture
2011	opened downtown Seattle retail store in Melrose Market
2011	designed and built state of art clam harvesting machine

and only exposed at low tide so managers have to understand the tides and schedule work accordingly. Many of these skills only come through doing them and would be difficult to learn in school even if classes were offered. Taylor Shellfish has promoted super workers with shellfish farming skills and intuition and provided them additional schooling to give them the math, computer and people skills to be effective managers.

Farming Milestones

Pioneered the use of hatchery clam seed on a large commercial scale; Realized a vision of the single oyster and the specialty oyster production and sales; Changed the perception and built the market for the "Mediterranean Mussel"; Developed commercial geoduck production and marketing into the most profitable intertidal farm species; Revolutionized hatchery seed production and farm timing with the move to winter production in Kona Hawaii.

Public Policy Milestones

Negotiated the $33 million Washington tribal settlement to benefit growers, Native American tribes and Washington's citizens; led the shellfish industry's engagement in state, national and global public policy for the last 15+ years; actively pursuing the next shellfish farming revolution, the move to third party sustainability certification; participated in updating the U.S. aquaculture policies and led the establishments and launch of National and Washington State Shellfish Initiatives.

The Taylor Family business continues to grow today, adding more areas to farm, increasing seed production, processing and sales capacity, and all the while working to grow the market for high quality shellfish in a way that benefits all growers and protects the environment. In recent years the focus has returned to expanding seed production with expansion of both the Kona hatchery and the Oakland Bay FLUPSY and the recent purchase of the Kuiper Mariculture shellfish nursery facility in California. At the same time the company is working to build new markets through sustainability certification, environmental public policy advocacy and a continued long term vision for the prosperity of their family, their employees and for the communities where they live and work.

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