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Erratum

Analysis of coastal and offshore aquaculture: Application of the FARM model to multiple systems and shellfish species

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ABSTRACT

The Farm Aquaculture Resource Management (FARM) model has been applied to several shellfish species and aquaculture types. The performance of the FARM model, developed to simulate potential harvest, key financial data, and water quality impacts at the farm-scale, was tested in five systems in the European Union: Loch Creran, Scotland (Pacific oyster), Pertuis Breton, France (blue mussel), Bay of Piran, Slovenia (Mediterranean mussel), Chioggia, Italy (Mediterranean mussel) and Ria Formosa, Portugal (Manila clam). These systems range from open coasts to estuaries, and are used for shellfish aquaculture by means of different cultivation techniques (e.g. oyster bottom culture in Loch Creran and mussel longlines and poles in Pertuis Breton).

The drivers for the FARM model were supplied by measured data, outputs of system–scale models or a combination of both. The results (given in total fresh weight) generally show good agreement with reported annual production (shown in brackets) at each farm: simulated production of 134 t of Pacific oyster in Loch Creran (150 t, −10%), 2691 t of blue mussel in Pertuis Breton (2304 t, +17%), 314 t of Mediterranean mussel in the Bay of Piran (200 t, +57%), 545 t of Mediterranean mussel in Chioggia (660 t, −17%) and 119 t of Manila clam in Ria Formosa (104 t, +15%).

The nitrogen mass balance for each farm was also determined with the FARM model. The net removal of nitrogen (N) by the farms was estimated to correspond to 1151 population equivalents per year (PEQ y^{-1}) in Loch Creran, 39505 PEQ y^{-1} in Pertuis Breton, 210 PEQ y^{-1} in the Bay of Piran, 7108 PEQ y^{-1} in Chioggia and 8748 PEQ y^{-1} in Ria Formosa. The aggregate income due to both the shellfish sale and substitution value of land-based fertilizer reduction or nutrient treatment was estimated to be about 680 k€ y^{-1} in Loch Creran, 14930 k€ y^{-1} in Pertuis Breton, 220 k€ y^{-1} in the Bay of Piran, 2560 k€ y^{-1} in Chioggia, and 5040 k€ y^{-1} in Ria Formosa.

Outputs of FARM may be used to analyse the farm production potential and profit maximization according to seeding densities and/or spatial distribution. Results of a marginal analysis for all the study sites were determined. As an example, profit maximization in Loch Creran was obtained with 97 t of seed, resulting in a total production of 440 t (profit of 2100 k€ for a culture period of about 2 years).

FARM additionally integrates the well-known ASSETS model, for assessment of farm-related eutrophication impacts. The assessment results for the five study sites show that water quality is either maintained or improved in all farms under standard conditions of culture practice.

FARM results may be used by farmers to analyse farm production potential and by managers for environmental assessment of farm-related water quality impacts, whether positive or negative. It is a useful tool for all stakeholders for the valuation of nitrogen credits, which may be traded as part of an integrated catchment management plan.

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The FARM results were scaled up to determine a net value of 3–7 billion € y^{-1} of ecosystem goods and services, provided by shellfish culture towards reducing eutrophication in the coastal waters of the European Union. These numbers highlight the role that extractive organic aquaculture plays in integrated coastal zone and nutrient emissions management.

1. Introduction

The sustainable use of marine resources has developed into a major concern for managers and regulators worldwide (e.g. Water Framework Directive 60/2000/EC (WFD) (EC, 2000); Marine Directive 2008/56/EC (EC, 2008); Biodiversity Strategy COM/98/0042 (EC, 1998); OSPAR 98/249/EC (EC, 1992a); Habitats Directive 92/43/EEC (EC, 1992b); Convention on Biological Diversity COM/92/509 (EC, 1992c) *Proposed* Offshore Aquaculture Act (NOAA, 2006); 25 different legislative instruments in China (Borja et al., 2008). Currently, one of the major issues is related to fisheries management, which "implies the regulation of the living resource's use based on the understanding of the structure and dynamics of the ecosystem of which the resource is part" (FAO, 1995). The increasing world demand for fishery products is not matched by increasing fishery captures, due to stock ruptures (e.g. Pauly et al., 1998). One potential solution lies in the increase of coastal aquaculture: China, the largest producer in the world, plans to substantially increase aquaculture production, in parallel with a reduction in capture fisheries to 90% of present day values by 2010, and 67% by 2020 (M.Y. Zhu, pers. com.).

Although the planned increase in coastal aquaculture may reduce the need for capture fisheries, it can potentially have negative environmental impacts (Black, 2001; Read and Fernandes, 2003; Sequeira et al., 2008), such as alteration of food webs and/or changes in productivity (López et al., 2008). Consequently, Jiang and Gibbs (2005) identified carrying capacity prediction as a pre-requisite to establishing or expanding large-scale culture operations. Ferreira et al. (2008a) propose that this should be carried out as a two-stage process, with an initial focus on the overall capacity of the system, and a second step to analyse suitability and impacts at the local scale. When compared to monoculture of finfish or shrimp, shellfish aquaculture has become very attractive (Gibbs, 2004) since it does not require artificial food input (Garen et al., 2004; Naylor et al., 2000). Furthermore, cultured bivalves provide a means of top–down control of eutrophication symptoms associated with excessive loading of nutrients to the coastal zone (Ferreira et al., 2007b; Xiao et al., 2007), although shellfish culture is not without its own environmental impacts (Chamberlain et al., 2001). It is likely that sustainable aquaculture expansion in western countries will tend to promote some form of Integrated Multi-Trophic Aquaculture (IMTA) (Neori et al., 2004), as is common in SE Asia, which combines, in the right proportions (see e.g. Li, 2007 for a review), the cultivation of fed aquaculture species (e.g. finfish), organic extractive aquaculture species (e.g. shellfish) and inorganic extractive aquaculture species (e.g. seaweeds).

It is currently accepted that the estimation of carrying capacity of coastal systems for aquaculture is constrained not only by the various definitions, which Inglis et al. (2000) classified into physical, production, ecological and social, but by important elements of scale (Ferreira et al., 2008a). Simulation models are an important tool for such assessments (see McKindsey et al., 2006; for a review) and the diversity and range of model applications clearly reflect the underlying scaling difficulties. Examples of these models include those focusing on shellfish growth (Dowd, 1997; Bacher et al., 1998; Campbell and Newell, 1998; Solidoro et al., 2000; Hawkins et al., 2002; Gangnery et al., 2004; Melia and Gatto, 2005), system–scale carrying capacity (Raillard and Ménesguen, 1994; Ferreira et al., 1998; Nunes et al., 2003; Grant et al., 2007; Jiang and Gibbs, 2005; Cerco and Noel, 2007; Marinov et al., 2007; Ferreira et al., 2008b), farm-scale carrying capacity (Bacher et al., 2003; Ferreira et al., 2007b), environmental impacts on cultivated species (Guyondet et al., 2005; Casas and Bacher, 2006) and aquaculture impacts on the environment (Munroe and McKinley, 2007; Ferreira et al., 2007b).

One key aspect in optimisation analysis of production at the farm-scale is the coupling of the biogeochemical drivers of growth and the representation of the population dynamics of simulated populations. Melia and Gatto (2005) presented a stochastic bioeconomic model for management of clam farming, where the shellfish growth model relies on a Von Bertalanffy approach, depending only on temperature and a growth coefficient. The omission of appropriate biogeochemical growth drivers makes it impossible to draw conclusions regarding effects of food depletion on growth, and consequences of farming for water quality.

The farm-scale assessment of production of the marketable cohort of shellfish, together with environmental budgeting of nutrients and consequences for eutrophication symptoms, requires the simulation of hydrodynamics, biogeochemistry, shellfish individual growth and population dynamics. Additionally, economic techniques such as marginal analysis must be applied in order to address profit maximization of aquaculture.

This work presents a development of the Farm Aquaculture Management Model (FARM — Ferreira et al., 2007b), and the validation results of the model as applied to five different shellfish aquaculture areas in the EU. The specific objectives of this work are:

1. To compare the results of aquaculture production simulations at widely differing sites in the EU, ranging from a loch in western Scotland to offshore areas in the Adriatic Sea, for a range of bivalve species;
2. To determine the consequences of shellfish aquaculture with a range of species, culture densities and cultivation techniques, as regards water quality, eutrophication and potential for nitrogen credit trading;
3. To contribute to the optimisation of culture practice at the different sites, based on profit maximisation, by means of economic analysis;

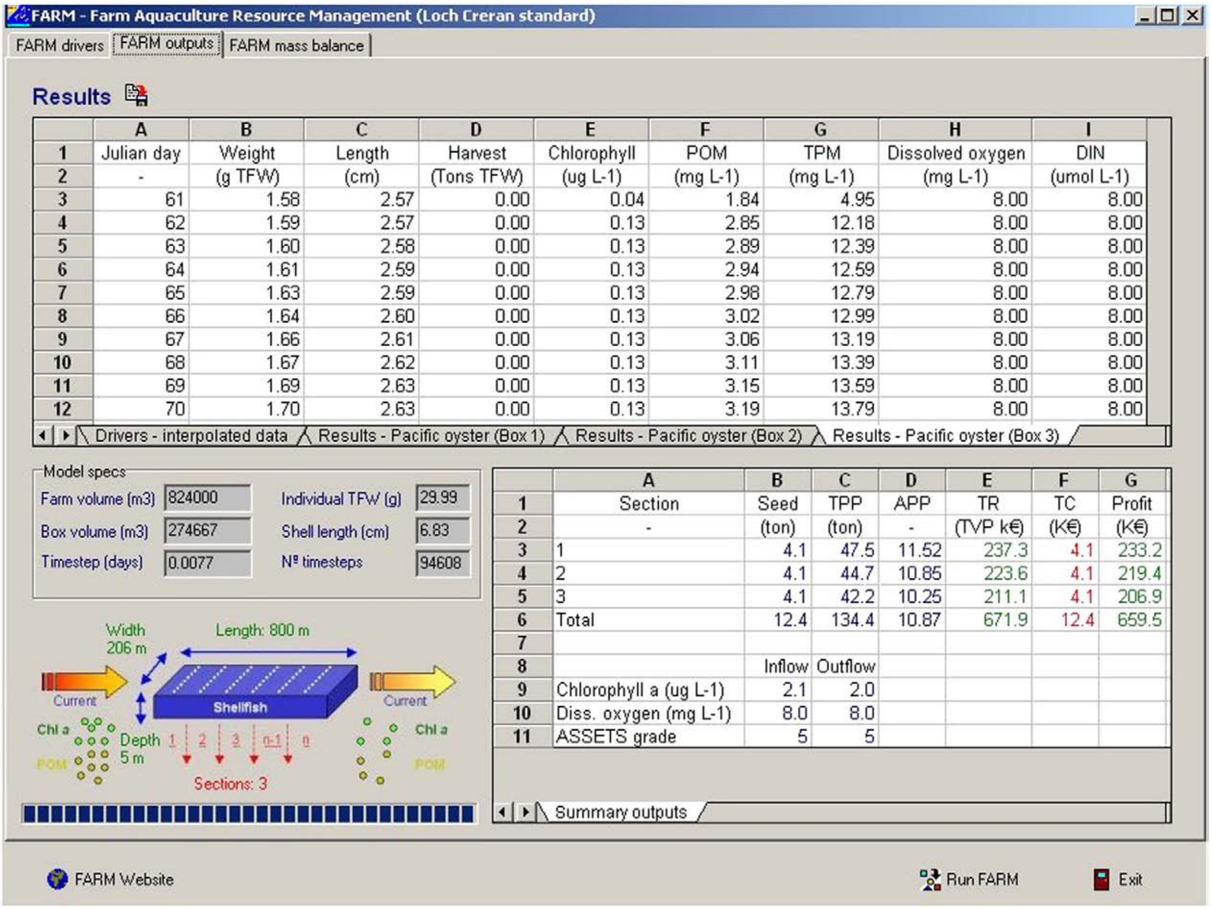
2. Methods

2.1. Methodological developments of the FARM model

The general characteristics and implementation of the FARM model have been described in Ferreira et al. (2007b), and will only be briefly indicated here, with an emphasis on new model developments.

The FARM model (Fig. 1) simulates processes at the farm-scale, by integrating a combination of physical and biogeochemical models, shellfish and finfish growth models and screening models for determining optimal production, income and expenditure, eutrophication assessment and nutrient emissions trading by means of a mass balance analysis. The input requirements of FARM may be divided into three groups:

(i) Time-series of drivers for environmental conditions such as water temperature and salinity, current speed, tidal regime, chlorophyll *a*, particulate organic matter (POM), total particulate matter (TPM) and dissolved oxygen;
(ii) Data on farm dimensions and positioning, existence of fish cages in IMTA scenarios, etc;
(iii) Cultivation practice (e.g. seed density, cultivation period and harvest weight).



	A	B	C	D	E	F	G	H	I
1	Julian day	Weight	Length	Harvest	Chlorophyll	POM	TPM	Dissolved oxygen	DIN
2	-	(g TFW)	(cm)	(Tons TFW)	(ug L-1)	(mg L-1)	(mg L-1)	(mg L-1)	(umol L-1)
3	61	1.58	2.57	0.00	0.04	1.84	4.95	8.00	8.00
4	62	1.59	2.57	0.00	0.13	2.85	12.18	8.00	8.00
5	63	1.60	2.58	0.00	0.13	2.89	12.39	8.00	8.00
6	64	1.61	2.59	0.00	0.13	2.94	12.59	8.00	8.00
7	65	1.63	2.59	0.00	0.13	2.98	12.79	8.00	8.00
8	66	1.64	2.60	0.00	0.13	3.02	12.99	8.00	8.00
9	67	1.66	2.61	0.00	0.13	3.06	13.19	8.00	8.00
10	68	1.67	2.62	0.00	0.13	3.11	13.39	8.00	8.00
11	69	1.69	2.63	0.00	0.13	3.15	13.59	8.00	8.00
12	70	1.70	2.63	0.00	0.13	3.19	13.79	8.00	8.00

Model specs
Farm volume (m3) 824000
Box volume (m3) 274667
Timestep (days) 0.0077
Individual TFW (g) 29.99
Shell length (cm) 6.83
Nº timesteps 94608

	A	B	C	D	E	F	G
1	Section	Seed	TPP	APP	TR	TC	Profit
2	-	(ton)	(ton)	-	(TVP k€)	(K€)	(K€)
3	1	4.1	47.5	11.52	237.3	4.1	233.2
4	2	4.1	44.7	10.85	223.6	4.1	219.4
5	3	4.1	42.2	10.25	211.1	4.1	206.9
6	Total	12.4	134.4	10.87	671.9	12.4	659.5
7							
8		Inflow	Outflow				
9	Chlorophyll a (ug L-1)	2.1	2.0				
10	Diss. oxygen (mg L-1)	8.0	8.0				
11	ASSETS grade	5	5				

Fig. 1. FARM™ model console layout showing the section for data outputs after application to the Loch Creran study site. The conceptual scheme (for rope and bottom culture) can be seen at the bottom left.

The web version of FARM (http://www.farmscale.org) does not currently provide as much functionality as the console version used for the work presented herein. Major differences in pre-processing and processing are (i) the incorporation of time-series; (ii) the possibility of specifying bi-directional current flow and explicit simulation of tidal height variation; and (iii) the possibility of combining finfish cage culture with shellfish cultivation. The post-processing provides a much more detailed analysis of model outputs, including financial data, and a full mass balance of nitrogen, together with annualised calculations of revenue from farming and from the potential sale of nutrient credits to other stakeholders.

A range of shellfish and finfish individual growth models is available for simulation in FARM. For the present work, growth of the Pacific oyster *Crassostrea gigas*, the blue mussel *Mytilus edulis*, and the Manila clam *Tapes philippinarum* were simulated using the ShellSIM model (http://www.shellsim.com) developed from that of Hawkins et al. (2002), and growth of the Mediterranean mussel *Mytilus galloprovincialis* was simulated using the model of Brigolin et al. (2009).

Rapid developments in the area of Rich Internet Applications (RIA) will allow a convergence of the features in both the console and web versions of FARM, though there is an important trade-off to consider between features and ease of use, particularly if the model is to remain targeted at the farming community.

3. Study sites

FARM was applied to five different systems (Fig. 2), ranging from bays to lochs, where different species and aquaculture techniques are being used.

A short description of each study site is given below and the main physical features of each are shown in Table 1. Only one aquaculture area (farm or group of farms) was considered in each system.

3.1. Loch Creran — Scotland

Loch Creran is a sea loch in the western highlands of Scotland (Fig. 2), with a total area of 15 km^2 and volume of 240 × 10^6 m^3. The loch has a maximum depth of 49 m and receives a mean freshwater input of 286 × 10^6 m^3 y^{-1}, mainly from the River Creran (Black et al., 2000).

Loch Creran has been used to a small extent for cultivation of Pacific oyster (100 t y^{-1}) and blue mussel (500 t y^{-1}). The FARM model was applied to a 16.5 ha oyster farm (Fig. 2), and run for a cultivation period of 730 days using an oyster seeding density of 50 ind m^{-2} (total seed: 12.36 t).

The outputs of daily averages for salinity, water temperature, oxygen, phytoplankton biomass, suspended particulate matter and organic particulate matter of the EcoWin2000 ecosystem model were used as inputs.

3.2. Pertuis Breton — France

Pertuis Breton, located on the French Atlantic coast (Fig. 2), is a macrotidal bay with an area of 350 km^2, a volume of 4950 × 10^6 m^3, and an average depth of 13.5 m (Stanisière et al., 2006). The average flushing time is 10 days. Mean freshwater inputs are estimated at 3110 × 10^6 m^3 y^{-1} and the hydrodynamics are controlled principally by the semi-diurnal tide (Garen et al., 2004).

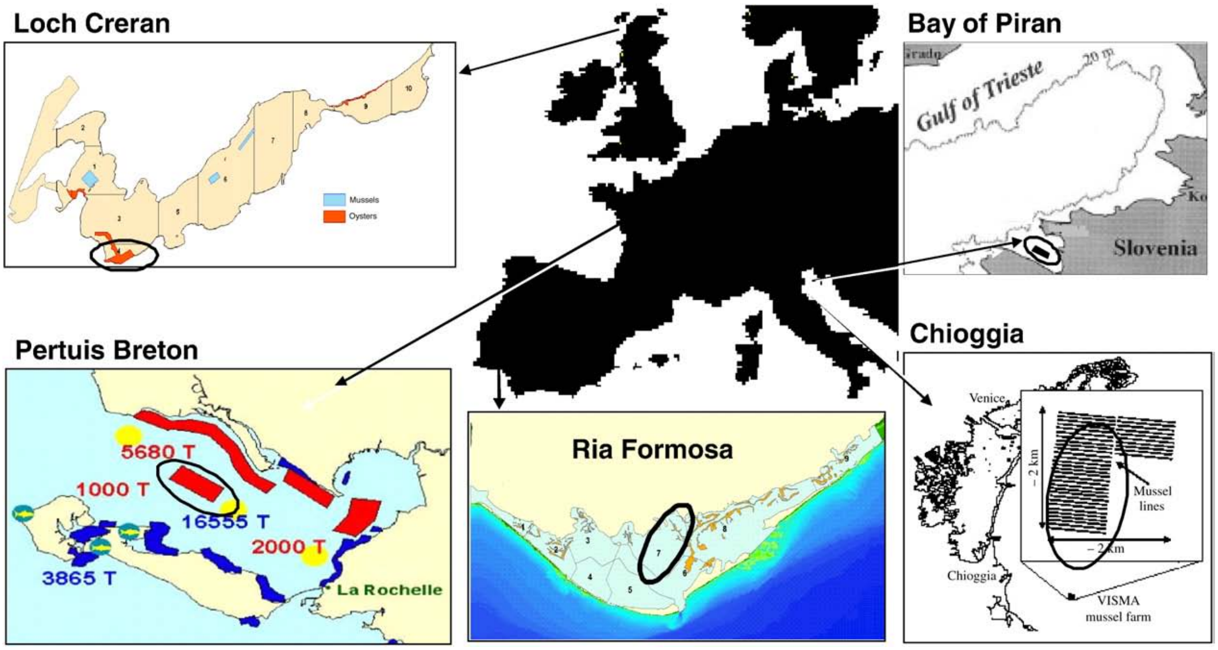


Fig. 2. Study sites location: Loch Creran (western Scotland), Pertuis Breton (western France), Ria Formosa (southern Portugal), Chioggia (north eastern Italy) and Bay of Piran (north western Slovenia). Black circles point to the aquaculture areas used to run FARM: Loch Creran — 206 m × 800 m × 5 m; Pertuis Breton — 800 m × 2500 m × 6 m; Bay of Piran — 180 m × 100 m × 7 m; Chioggia — 1000 m × 2000 m × 7 m; Ria Formosa — 71 m × 1600 m × 3 m.

Blue mussels are cultivated either by intertidal pole culture or by longline culture, with a production of up to 10,000 t y^{-1} (Garen et al., 2004).

FARM was applied to a 200 ha longline farm (Fig. 2). Field data were used as inputs and the model was run for a culture period of 435 days, and for a mussel density of 166 ind m^{-2} (total seed: 664 t).

3.3. Piran — Slovenia

The Bay of Piran is a shallow basin with an area of 19 km^2, situated in the Gulf of Trieste, in the northern Adriatic Sea (Fig. 2). Mediterranean mussels are produced in a small area of this bay; for the purpose of this simulation, a 1.8 ha longline farm was used (Fig. 2).

3.4. Chioggia — Italy

The farm area is situated approximately 5 miles south of the city of Chioggia (Fig. 2), on Italy's Adriatic coast, and can be considered an offshore aquaculture site, with a water column depth of 20–24 m. The Mediterranean mussel is grown on longlines with an average production of about 600 t $year^{-1}$ (Brigolin et al., 2009). For the present work, a 200 ha farm was simulated (Fig. 2).

3.5. Ria Formosa — Portugal

The Ria Formosa is a hypersaline barrier island lagoon system on the south coast of Portugal (Fig. 2), with an area of 49 km^2 and a volume of 92×10^6 m^3. It is an inverse estuary, with negligible freshwater inputs and a semi-diurnal tidal exchange which significantly exceeds the residual volume. The Ria has a wide range of uses, including tourism, extraction of salt and sand, fisheries, and aquaculture. Clam cultivation provides a yield of about 8000 t of total fresh weight (TFW) per year.

In this system, the FARM model was applied to a 11.34 ha clam farm (Fig. 2). The drivers for the model were obtained from a combination of field measurements and system–scale model outputs. A cultivation period of 180 days and a clam seeding density of 90 ind m^{-2} (15.34 t) were used.

Input data for FARM are shown in Table 2 for all study sites. Field data were used for Pertuis Breton, Chioggia and Piran, whilst previously

Table 1
Main physical characteristics of the five study sites.

System		Loch Creran	Ria Formosa	Pertuis Breton	Chioggia	Bay of Piran
Volume ($\times 10^6$ m^3)		240	92	4920	–	212
Area (km^2)		15	49	350	–	19
Maximum depth (m)		47	~2	54 (mean: 13.5)	24	24
Temperature (°C)		6–15	13–28	8–20	5–26	6–28
Salinity		30–33	34–39.5	30–35	36–38	28–40
River flow (m^3 s^{-1})		9.1	3	<100	–	1.78
Water residence time (d)		~6	0.5 – 2	10	0.2	–
Total culture area (ha)	Mussel	18.82	–	200	300	1.8
	Clam	–	485	–	–	–
	Oyster	31.46	–	25	–	–
Percentage area used for shellfish culture (%)		3.35	1.47	0.057	–	0.1

Table 2
FARM model setup data for the five study sites.

	Loch Creran	Pertuis Breton	Bay of Piran	Chioggia	Ria Formosa
Farm layout					
Width (m)	206	800	180	1000	71
Length (m)	800	2500	100	2000	1600
Depth (m)	5	6	4	7	3
Culture structures	Trestles (intertidal, 1.8 m above datum)	Longlines	Longlines	Longlines	Bottom
Environment					
Current speed					
Spring (m s^{-1})	0.2	0.53	0.1	0.2	0.8
Neap (m s^{-1})	0.1	0.1	0.015	0.1	0.3
Tidal regime	Semi-diurnal	Semi-diurnal	Semi-diurnal	Semi-diurnal	Semi-diurnal
Tidal range					
Spring (m)	3	5.45	–	–	–
Neap (m)	2	2.11	–	–	–
Mid-tide (m)	2	3.63	–	–	–
Shellfish cultivation					
Species	Pacific oyster	Blue mussel	Mediterranean mussel	Mediterranean mussel	Manila clam
Density (ind. m^{-2})	50	166	1089	100	90
Mortality (y^{-1})	10%	20%	1%	10–15%	66%
First seeding day	61	90	246	193	90
Culture period (d)	730	415	450–540	308	180
Seed weight (g)	1.5	2	2.2	3.3 ± 0.6	1.5
Harvest weight (g)	80	15	15.4	20.7 ± 6.8	10
Seed cost € kg^{-1}	1	0.08	0.7–1	0.35	1
Sale price € kg^{-1}	5	1.3	0.5–0.6	0.6–0.7	10

validated outputs of the EcoWin2000 system–scale model were used for Loch Creran (Sequeira et al., 2008) and Ria Formosa (Nobre et al., 2005).

4. Results and discussion

Results are presented below for the five farms simulated in the model, with an emphasis on production, impact of shellfish aquaculture on water quality and eutrophication, and marginal analysis for profit maximisation.

4.1. Production

Production records and simulation results obtained in FARM are presented in Table 3.

The application of the FARM model in Loch Creran yielded a total production of 134.4 t of oysters. The ecosystem model results (used for providing the drivers to the FARM model) estimated a total production of 155 t of oysters. In both models, the scope for growth determines both the harvestable biomass, by means of a population dynamics model (see Ferreira et al., 2008b), and the weight of an individual animal. The system–scale EcoWin2000 model gave an individual weight of 80 g, but in FARM only a lower individual weight could be obtained. The reported annual harvest in Loch Creran is estimated to be about 150 t TFW, mostly obtained from this farm (H. Vaik, pers. com.), ie. the farm-scale model underestimates the reported harvest by about 10%.

Table 3
Harvest records and FARM model production results in the five study sites.

System		Loch Creran	Pertuis Breton	Bay of Piran	Chioggia	Ria Formosa
Species		Pacific oyster	Blue mussel	Med. Mussel	Med. mussel	Manila clam
Records	Production (ton)	155[a]	2304	200	660	104[a]
Model results	Production (ton)	134.4	2691	314	545	119.3

[a] Production data for this system was obtained using the EcoWin2000 ecological model.

In Pertuis Breton, a total production of 2690.9 t of blue mussels was estimated by the model for the 200 ha farm being simulated, about 17% more than the reported harvest.

In the Bay of Piran (Slovenia) and in the Chioggia region (Italy), where Mediterranean mussels are cultivated offshore using longlines, the FARM model appears to overestimate the reported harvest in the first case (+57%), but agrees well in the second (+10%). In both cases, the production is overestimated, but the reported mortality in the Bay of Piran farm (1%, Table 2) seems extremely low. Since shellfish mortality is a forcing function within FARM, and one to which the model is fairly sensitive (e.g. increasing mortality to 10% decreases the harvest from 314 to 296 t), that is a possible cause for the overestimate in production. This is reinforced by the fact that the individual weights given in the model (~15 g) match the reported data very well, which suggests that the drivers of growth are appropriately simulated. An additional possibility is that the reported density (over 1000 ind. m^{-2}, Table 2), which also seems extremely high, is being reduced over the culture cycle due to rope thinning. A reduction in mussel density to 750 ind. m^{-2} results in a final yield of 257 t TFW.

No specific farm harvest data were available for the Ria Formosa, which makes it difficult to judge the performance of the FARM model. Annual harvests of Manila clam for the entire Ria are reported to be about 8000 t, a result which is well matched in the EcoWin2000 system–scale model (Nobre et al., 2005). The outputs for clam production in the model box where the simulated farm is located were used to calculate the yield (104 t, Table 3) corresponding to that particular farm, assuming identical yield for the whole area farmed in that box. A total production of about 120 t of clams was estimated in FARM, which is in good agreement (+15%) with this value. However, better field data are required to validate these results.

Overall, model outputs appear to be well matched to the available data, particularly considering the range of systems and species studied.

4.2. Water quality and eutrophication

FARM performs an automated carbon and nitrogen mass balance based on the net removal of these elements from the system. The gross removal due to the ingestion of phytoplankton and detrital organic

Table 4
Mass balance and assessment of nutrient emissions trading in the five study sites using FARM.

Species		Loch Creran	Pertuis Breton	Bay of Piran	Chioggia	Ria Formosa
		Pacific oyster	Blue mussel	Mediterranean mussel		Manila clam
Phytoplankton removal (kgC y^{-1})		745	199981	21538	171560	3457
Detritus removal (kgC y^{-1})		59483	1627710	19015	334659	321271
N removal (kg y^{-1})	Phytoplankton	−116	−31108	−3350	−26687	−538
	Detritus	−9253	−253199	−2958	−52058	−49975
	Excretion	165	10269	2938	23627	142
	Faeces	5298	142504	2674	31371	21405
	Mortality	10	1169	4	292	100
	Mass balance	−3797	−130365	−692	−23456	−28867
Population equivalents (PEQ y^{-1})		1151	39505	210	7108	8748
Income (k€ y^{-1})	Shellfish farming	335.9	3076.7	154.9	429.1	2418.2
	Nitrogen removal	345.2	11851.4	62.9	2132.3	2624.3
	Total	681.1	14928.1	217.8	2561.4	5042.5

material by shellfish filtration is reduced by the return of these materials through excretion and elimination. While the carbon mass balance is useful for examining the role of organic extractive aquaculture on the global carbon budget, the nitrogen mass balance is of direct relevance to coastal management on a local scale, particularly for integrated coastal zone management (USEPA, 2001; Lindahl et al., 2005; EPA; Ferreira et al., 2007b). Results for the five systems are shown in Table 4, and the discussion that follows is mainly centred on associated nitrogen budgets, together with implications for nutrient credit trading in Integrated Coastal Zone Management.

Shellfish farms can help reduce eutrophication symptoms (e.g. Lindahl et al., 2005; Ferreira et al., 2007c) by removing chlorophyll, thereby increasing water clarity, which promotes growth of Submerged Aquatic Vegetation (SAV) and reducing the decomposition of organic material, which in turn reduces secondary eutrophication symptoms such as oxygen depletion (Bricker et al., 2003; Ferreira et al., 2007a). Results from the application of the ASSETS model (Table 5) implemented in FARM to provide a eutrophication indicator at the local scale, are examined for the various systems.

In Loch Creran, results from FARM show a gross removal of 0.1 t N y^{-1} contained in phytoplankton and 9.2 t N y^{-1} in detritus, due to oyster culture. This corresponds to a net nitrogen removal of 1151 population equivalents (PEQ) per year, which would otherwise require changes to agricultural practices to reduce emissions, or land-based treatment to provide a similar water quality. The combined value of income from shellfish sales (336 k€) and the substitution cost of nutrient treatment (345 k€) is calculated in the model as 681 k€ y^{-1}. The ASSETS model, integrated in FARM, indicates that the quality status of the outflowing water from the Loch Creran farm is *Good* (sensu WFD), but the grade remains unchanged when compared to the inflow, partly due to the relatively low cultivation density, which does not cause much food depletion.

The Pertuis Breton and Chioggia farms showed the highest nitrogen removal of all farms simulated, with annualised gross removals of about 31 and 253 t y^{-1} respectively, corresponding globally to over 39,000 PEQ, which is equivalent to the nitrogen loss from about 8000 ha of agricultural land (Johnes, 1996). There is a scaling factor (1 m^2 farm: 1 m^2 agriculture) of 20–25 for all the farms, excluding Ria Formosa. This factor varies between 14 (Loch Creran) and 150 (Ria Formosa), due to both the variability in farms (density, species, mortality, etc) and environmental drivers (food availability and depletion, proportion of detrital organic matter, etc).

In contrast to Loch Creran, Chioggia, Pertuis Breton and the Ria Formosa, where the ASSETS grade does not change due to the shellfish filtration, the eutrophication indicator score shows that aquaculture farms have significant positive effects on water quality in the Bay of Piran, where the quality increases from *Moderate* to *Good* status (Table 5). In all the systems, the eutrophication indicator at the farm outlet is at Good status or higher, thereby fulfilling the requirements of the EU WFD.

In the Ria Formosa, a net total of about 28.9 t y^{-1} of nitrogen (Table 4) are removed from the water through filtration of algae and detritus, and the mass balance is illustrated in Fig. 3.

The diagram is only shown for this system, but similar representations may be made for any of the other farms. Phytoplankton removal is two orders of magnitude lower than detrital POM, and the potential income from harvest and from the substitution of land-based nutrient removal is about equal. However, this analysis needs to be carefully interpreted, because if primary symptoms of eutrophication are mainly excessive growth of opportunistic seaweeds such as *Ulva* or *Enteromorpha*, then the value of the shellfish farm contribution to reducing eutrophication symptoms will be overestimated. This is particularly the case in systems with short water residence time (<5 days), where autochtonous phytoplankton blooms are unlikely to occur (Ferreira et al., 2005). The high annual mortality (66%) imposed on this model reflects such macroalgal blooms, which can smother clam beds and cause local anoxic conditions, with consequent losses to the shellfish industry. In coastal lagoon systems with higher residence times, the role of filter-feeders in reducing both pelagic and benthic eutrophication systems is easier to justify, since the micro-algae and detritus have an opportunity to mineralise within the lagoon itself, potentially causing secondary blooms of macroalgae.

By estimating the nutrient removal from typical farms within a system, an estimate of the total nutrient removal can be made, which is an indicator of the role of shellfish in the overall processing of organic material. As an example, in the Ria Formosa, where the simulated farm produces about 120 t of clams per year, the net overall nitrogen removal scaled to the whole system corresponds to

Table 5
ASSETS results obtained for the 5 farms.

System	Percentile 90 chl a (μg L^{-1})	Percentile 10 O_2 (mg L^{-1})	ASSETS score
Loch Creran	🟦 -0.1 → 🟦	🟩 0.0 → 🟩	🟦 High → 🟦
Pertuis Breton	🟩 0.5 → 🟩	🟦 = → 🟦	🟩 Good → 🟩
Bay of Piran	🟩 -4.3 → 🟦	🟨 -0.1 → 🟨	🟨 Good → 🟩
Chioggia	🟦 -0.2 → 🟦	🟩 -0.1 → 🟩	🟦 High → 🟦
Ria Formosa	🟦 -0.1 → 🟦	🟩 -0.1 → 🟩	🟦 High → 🟦

The ASSETS colour grades (corresponding to the WFD scale: blue — High, green — Good, yellow — Moderate, orange — Poor, and red — Bad) show the score for the symptom in the inflowing water on the left, outflow on the right. Concentration changes to eutrophication symptoms are shown in blue (Better), red (Worse).

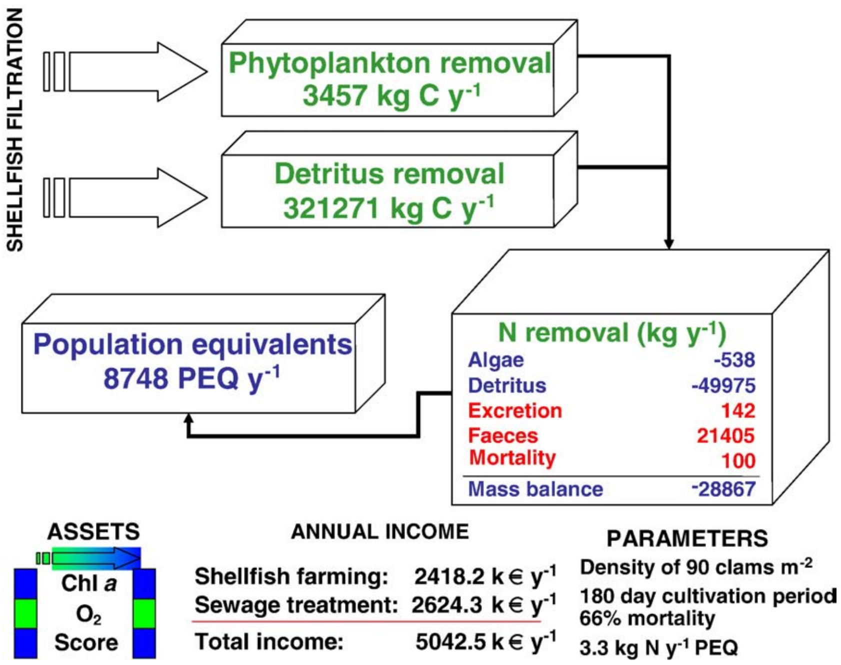


Fig. 3. Mass balance and nutrient emissions trading for clam aquaculture in Ria Formosa.

approximately 1900 t y^{-1}, i.e. a PEQ of about 580,000, or an agricultural area of about 115,000 ha, about 15% of the total catchment area.

The calculation of the economic value of substituting land-based treatment or fertilizer reductions by top–down control by filter-feeders sets an upper limit on the value of nitrogen credits which may potentially be sold by shellfish aquaculture farmers to agriculture or industry, with the objective of offsetting nitrogen emissions, in exactly the same way as is currently traded for carbon. These credits may also be traded within the waterbody itself, with the finfish farming community, with the objective of reducing the impact of particulate emissions from fish cages. Recent work in Sanggou Bay, China (Ferreira et al., 2008a) showed that simulated culture of oysters and finfish in IMTA resulted in a 75% increase in both oyster production and nitrogen removal, a clear benefit both for the oyster farmer and the finfish farmer. Within the farm area itself, the business model may be developed either in financial terms or as a mixed trading model whereby both types of culture are symbiotic. Nitrogen (or phosphorus, depending on the limiting nutrient for primary production) trading has an advantage over carbon in that it is an example of local management, which can be implemented at the catchment scale, and readily understood by all stakeholders. In a number of regions within the EU and elsewhere, where nutrient pressure on the coastal zone is essentially due to diffuse sources from agriculture, there is little scope to impose further land-based emission controls without bankrupting the farming sector. Under such circumstances, it makes good economic sense to examine complementary management structures, and to develop and test the tools necessary for evaluating the effects and valuating the markets.

Table 6
Synthesis of the FARM economic analysis for the profit maximization scenario in each study site (Pi =Price of input and Po = Price of output).

	Loch Creran	Pertuis Breton	Bay of Piran	Chioggia	Ria Formosa
Pi (€ kg^{-1})	1	0.08	0.85	0.35	1
Po (€ kg^{-1})	5	1.3	0.55	0.6 – 0.7	10
Seed (tons TFW)	97	2240	45.5	396	340
TPP (tons TFW)	440	3431	317.7	475.2	910
APP	4.5	1.53	6.98	1.2	2.7
MPP	0.20	0.06	1.55	0.54	0.10
Profit (k)	2100	4281	245	170.3	8760

4.3. Economic analysis

A marginal analysis of the optimal profit for each farm, determined by running multiple seeding density scenarios (Jolly and Clonts, 1993; Ferreira et al., 2007b) at each site, is shown in Table 6.

Production as Total Physical Product (TPP), Average Physical Product (APP, output/input) and Marginal Physical Product (MPP, the first derivative of the TPP curve) were calculated for each series. Optimal profits, at which the Value of the Marginal Product, VMP, is equal to P_x, the unit cost, are shown (Table 6) for each farm, and a general comparison of the present-day farming and the optimal situation is shown in Table 7.

A detailed representation of the marginal analysis is illustrated for Loch Creran in Table 8 and Fig. 4. The table shows the results for TPP,

Table 7
Comparison of present situation and profit maximization scenarios for the five study sites (ASSETS scores which change are underlined).

Study site	Loch Creran	Pertuis Breton	Bay of Piran	Chioggia	Ria Formosa
Farm area (ha)	16.5	200	1.8	200	11.4
Present setup					
Seed (tons)	12.4	664	43.1	660	15.3
TPP (tons)	134.4	2322	314	545	119
TPP (tons ha^{-1})	8.1	11.6	174.4	2.7	10.6
Harvest profit (k€)	659.5	3445	243	123	1177
PEQ y^{-1}	1151	39505	210	7108	8748
ASSETS score	High	Good	Good	High	High
Harvest income (k€ y^{-1})	335.9	3076.7	154.9	419.4	2418.2
Total income (k€ y^{-1})	681.1	14928.1	217.8	2561.4	5042.5
Profit maximisation					
Seed (tons)	97	2240	45.5	396	340
TPP (tons)	440	3431	317.7	475.2	910
TPP (tons ha^{-1})	26.7	17.15	176.5	2.4	80
Harvest profit (k€)	2100	4281	~245	~170.3	8760
PEQ y^{-1}	7846	55266	215	4444	95092
ASSETS score	High	High	Good	High	Good
Harvest income (k€ y^{-1})	1100	3923	201.1	366	18450.5
Total income (k€ y^{-1})	3454.4	20481.7	221.1	1645.9	46978.1

APP, MPP and other data, based on a set of 11 seeding scenarios. These results were used to determine the optimal value for seeding, derived from the VMP. For the loch as a whole, this occurs at seeding densities of about 97 t (8× higher than the current seeding densities).

The TPP resulting from these seeding densities was estimated to be 440 t, with a profit of about 2100 k€, and at the optimal point the APP = 4.5, indicating that harvestable biomass is over 4× the seeded biomass.

Pertuis Breton shows a very low optimal MPP, due to the negligible seed price. In contrast, the Bay of Piran's optimal MPP is greater than one. Values exceeding unity mean that the farm can only make a profit if the APP is high, as occurs in this system. In Piran, the current APP of 7.3 is reduced only slightly to 7 under optimal profit conditions, with only a 1% increase from 314 to 317 t produced. Of the five farms studied, Piran is the most efficiently operated, in terms of profit optimisation. Furthermore, this farm also shows a positive change in the ASSETS grade from *Moderate* to *Good*, at the present (near-optimal) seeding density. This is an additional benefit, particularly when considering that the Moderate/Good boundary is a critical threshold of the WFD.

The simulated farms in Loch Creran, Pertuis Breton and Ria Formosa are all cultivated at seeding densities well below that which allows profit optimisation, but in Chioggia, the reverse situation appears to occur. In the latter system, FARM results indicate that the ideal seed application for maximal profit is about 60% of current practice. The implication is that aquaculture in Chioggia is presently driven by income maximisation, rather than profit. Such an optimisation due to a 40% reduction in seed would result in only a 13% decrease in income, but would increase the APP from the present day 0.82 (i.e. APP < 1, therefore the profit stems only from price differential) to a positive value of 1.2, where output tonnage exceeds seed. The reduction in seed will have adverse consequences on the role of the farm in mitigating eutrophication symptoms, due to lower filtration of POM: there is a reduction in the PEQ value from about 98,000 to 61,000. However, the benthic footprint resulting from deposition of mussel faeces and pseudofaeces (not currently simulated by FARM) will also be reduced, which will alleviate pressure on dissolved oxygen in the bottom waters, particularly in this area of relatively slow water currents, when compared to most of the other sites.

Of the five systems, the Ria Formosa farm appears furthest from its potential profit optimum, with plenty of apparent scope for an increase in seeding density, since the TPP at the maximum profit point is almost eight times the current production. Nevertheless, this interpretation must be taken with care, due to (a) other factors such as disease occurrence at high densities; and (b) increased mortality due to oxygen depletion. At the optimal profit point the seed density reaches almost 2000 ind. m^{-2}, and although the percentile 10 dissolved oxygen concentration in the outflow is 4.8 mg L^{-1}, the minimum value is 4.6 mg L^{-1}. The overall ASSETS rating for the farm shifts from *High* to *Good* status, because the (tenth percentile) O_2 concentration falls into the biological stress (<5 mg L^{-1}) category. In addition, dissolved oxygen (in this case monthly measurements, which FARM interpolates linearly to provide daily driver data) is commonly measured in daytime, rather than at night when values may be significantly lower. For that reason, although the FARM model results certainly show scope for higher production and improved return on investment, increases in seed density need to be well grounded in the precautionary principle. These general aspects apply to the various study sites, and suggest that when considering the elevation of seed densities for optimal profit, analyses of potential detrimental effects are strongly recommended. For example, the Ria Formosa, like Loch Creran, Carlingford Lough (Ireland), Jiaozhou Bay (China) and many other systems, has a significant amount of intertidal culture, and oxygen depletion and consequent bivalve mortality during low water, particularly in warmer periods, is an important consideration: excessive stocking may constitute a tipping point.

Table 8

Production and economic parameters for different seeding densities in Loch Creran (price of input (Pi) = 1 € kg − 1; price of output Po = 5 € kg − 1).

Seed (ton)	TPP (ton)	APP	MPP	TR (k€)	TC (k€)	Profit (k€)
0	0	0	0	0	0	0
2.5	29.7	12.02	11.9	148.5	2.5	146
6.2	71.5	11.6	11.3	357.7	6.2	351.5
12.4	*134.4*	*10.87*	*10.15*	*671.9*	*12.4*	*659.5*
24.7	236.8	9.58	8.33	1184	24.7	1159
37.1	312.4	8.43	6.10	1562	37.1	1525
49.4	366.2	7.41	4.37	1831	49.4	1782
61.8	402.4	6.51	2.92	2012	61.8	1950
74.2	424.9	5.73	1.81	2125	74.2	2050
86.5	436.7	5.05	0.96	2184	86.5	2097
91.5	439	4.8	0.46	2195	91.5	2104
100.1	440.4	4.4	0.16	2202	100.1	2102
105.1	439.9	4.19	−0.1	2199	105.1	2094

Present seeding in italic, seeding for maximum profit underlined.

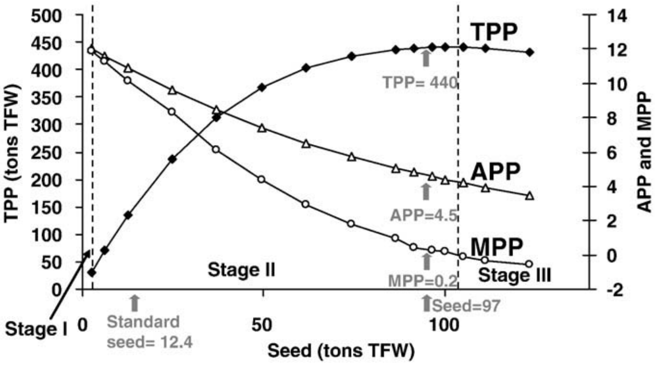


Fig. 4. Economic analysis for oyster cultivation in Loch Creran with a cultivation period of 730 days.

5. Conclusions

The analysis of shellfish production in farms rearing major species cultivated in the EU, USA and many other parts of the world, reflecting different types of culture, over a latitudinal range of twenty degrees, was carried out by means of the FARM model. In general, predictions are in good agreement with reported production values. This suggests that a model which uses input data which are relatively simple and inexpensive to acquire may nevertheless be a strong decision-support tool for growers and regulators alike.

One of the limitations of earlier versions of the model (Ferreira et al., 2007b) was the lack of bidirectional water circulation. This has been added, and tested on some of the systems reported in this paper. In general, the effect of introducing this additional level of complexity, which requires driver data for ebb and flood conditions, is small in terms of overall production. It is therefore an option that may be exercised at the discretion of the user. A better description of the variability of water current velocities, emersion and immersion of cultivated tidal flats, and other enhancements, most notably the use of interpolated driver data rather than constant values, all contribute to increase the accuracy of the model and confidence in its results. The trade-off is the loss of simplicity which was the hallmark of the earlier version of FARM, which perhaps accounts for the fact that the website (http://www.farmscale.org) registered visits over the last year from 64 countries, in all continents where shellfish aquaculture takes place. Consequently, two layers of complexity will still be offered, trading off some accuracy for ease of use.

The use of FARM for marginal analysis combines hydrodynamics, biogeochemistry, population dynamics, and economics into a powerful management tool. Typically, economic tools of this nature require as input a "biological production function", which is in practice what FARM offers through the application of its underlying physical, physiological and ecological models. The type of curve shown in Fig. 4 requires about 10–15 seeding scenarios to be run, in order to determine the shape of the TPP curve, i.e. the production function, and the derived APP and MPP curves, which allow a farmer to simulate both return on investment (APP) and profit maximisation (MPP). Experimentally, it takes 12–13 years to obtain 10 points on the production function curve for a 3 year cultivation cycle, which is an unacceptable time frame for business purposes, and thus has high social costs. Moreover, there is no guarantee that such an "experimental plot" approach scales to a larger area due to the changes in current flow, food depletion and other factors. These considerations substantially increase the appeal of a simulation modelling alternative.

Because the farms simulated in this work reflect the spectrum of shellfish aquaculture in the EU, some general conclusions may be drawn from upscaling the local-scale results to European aquaculture as a whole. A total EU production of 1051×10^3 t y^{-1} (FAO, 1999), scaled from 1997 using an annual growth rate of 3.4%, was estimated for the major cultivated bivalves. Of these, 70% are mussels (54% blue mussel and 16% Mediterranean mussel), 23% are oysters and 7% are clams. Data from Tables 3 and 4 were used to provide global estimates of the role of EU shellfish farms in removing nutrients and indicate that it corresponds to a removal of almost 57,000 t of nitrogen per year, i.e. a population equivalent of 17 million people, the population of the Netherlands. The substitution value for land-based nutrient removal is estimated at around 5 billion € y^{-1}, or 3% of the Gross Domestic Product (GDP) of Portugal.

Although these numbers are probably better represented by a range incorporating a margin of error of $\pm 20\%$, i.e. 3–7 billion € y^{-1}, they do supply a clear order of magnitude indicator of the net value of ecosystem goods and services provided by shellfish culture in reducing eutrophication in the coastal zone, and highlight the role that it plays in integrated coastal zone and nutrient emissions management.

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