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ScienceDirect
Aquaculture
Aquaculture 264 (2007) 160 – 174
www.elsevier.com/locate/aqua-online

Management of productivity, environmental effects and profitability of shellfish aquaculture — the Farm Aquaculture Resource Management (FARM) model

J.G. Ferreira [a,*], A.J.S. Hawkins [b], S.B. Bricker [c]

[a] *IMAR — Institute of Marine Research, Centre for Ecological Modelling, IMAR–DCEA, Fac. Ciencias e Tecnologia, Qta Torre, 2829-516 Monte de Caparica, Portugal*
[b] *Plymouth Marine Laboratory, The Hoe, Plymouth PL1 3DH, Devon, United Kingdom*
[c] *NOAA — National Ocean Service, National Centers for Coastal Ocean Science, 1305 East West Highway, Silver Spring, MD 20910, USA*

Received 24 August 2006; received in revised form 29 October 2006; accepted 6 December 2006

Abstract

This paper describes a model for assessment of coastal and offshore shellfish aquaculture at the farm-scale. The Farm Aquaculture Resource Management (FARM) model is directed both at the farmer and the regulator, and has three main uses: (i) prospective analyses of culture location and species selection; (ii) ecological and economic optimisation of culture practice, such as timing and sizes for seeding and harvesting, densities and spatial distributions (iii) environmental assessment of farm-related eutrophication effects (including mitigation).

The modelling framework applies a combination of physical and biogeochemical models, bivalve growth models and screening models for determining shellfish production and for eutrophication assessment. FARM currently simulates the above interrelations for five bivalve species: the Pacific oyster *Crassostrea gigas*, the blue mussel *Mytilus edulis*, the Manila clam *Tapes phillipinarum*, the cockle *Cerastoderma edule* and the Chinese scallop *Chlamys farreri*. Shellfish species combinations (i.e. polyculture) may also be modelled.

We present results of several case studies showing how farm location and practice may result in significant (up to 100%) differences in output (production). Changes in seed density clearly affect output, but (i) the average physical production decreases at higher densities and reduces profitability; and (ii) gains may additionally be offset by environmental costs, e.g. unacceptable reductions in dissolved oxygen. FARM was used for application of a Cobb–Douglas function in order to screen for economically optimal production: we show how marginal analysis can be used to determine stocking density. Our final case studies examine interactions between shellfish aquaculture and eutrophication, by applying a subset of the ASSETS methodology. We provide a tool for screening various water quality impacts, and examine the mass balance of nutrients within a 6000 m^2 oyster farm. An integrated analysis of revenue sources indicates that about 100% extra income could be obtained by emissions trading, since shellfish farms are nutrient sinks. FARM thus provides a valuation methodology useful for integrated nutrient management in coastal regions.

The model has been implemented as a web-based client–server application and is available at http://www.farmscale.org/.

Keywords: Shellfish carrying capacity; Screening model; Farm-scale management; Aquaculture; Eutrophication; Nutrient trading

* Corresponding author. Fax: +44 20 7691 7827.
E-mail address: joao@hoomi.com (J.G. Ferreira).

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doi:10.1016/j.aquaculture.2006.12.017

1. Introduction

Shellfish aquaculture is of great importance worldwide, with production increasing at an average of 7.8% per annum over the last 30 years (FAO, 2004), stimulated by market demand and by legislative initiatives such as the proposed U.S. Offshore Aquaculture Act (NOAA, 2006). The potential diversity of cultivated species (e.g. oysters, mussels, scallops, clams), each with different environmental adaptations, the pressure towards optimising species combinations within polyculture and integrated multi-trophic aquaculture (IMTA) (Fang et al., 1996; Nunes et al., 2003; Neoria et al., 2004) and the technical developments that increasingly afford suspended "pelagic" habitats in addition to bottom culture together provide significant challenges to sustainable management. These challenges are made more acute by pressures for further expansion in an industry whose production has doubled every 15 years in the recent past.

Assessments of sustainable mariculture in general and shellfish culture in particular are conditioned by different definitions of carrying capacity, which may be regarded as physical, production, ecological and social (Inglis et al., 2000). These are themselves modulated by scaling, usually considered to be either system scale (bay, estuary or sub-units thereof), or local scale (farm). McKindsey et al. (2006) provide a critical review of methods, including models, used for evaluating these various types of carrying capacity.

System-scale management of shellfish aquaculture requires a top-down assessment of carrying capacity, and has many similarities to any other large-scale plan for optimising the multiple uses of goods and services. Models (of varying complexity) that address system-scale issues include those of Carver and Mallet (1990), Raillard and Ménesguen (1994), Ferreira et al. (1998), Gangnery et al. (2001) and Nunes et al. (2003). At the local scale, the evaluation of potential fish aquaculture sites has also been supported by models such as DEPOMOD (Cromey et al., 2002) and MOM (Stigebrandt et al., 2004), but there are very few models for analysis of shellfish farms. Most recently, Bacher et al. (2003) combined a hydrodynamic model, measured data on food concentration and the simulation of individual shellfish growth to optimise density according to biological production alone.

Environmental influences of bivalve filter-feeders have been discussed by many authors (e.g. Cloern, 1982; Gerritsen et al., 1994; Lucas et al., 1999), and are most likely to be seen in systems dominated by aquaculture (Nobre et al., 2005). Effects may include a top-down control of eutrophication symptoms (*sensu* Bricker et al., 2003), when selective filtration may additionally influence the composition of phytoplankton species (Shumway et al., 1985; Bougrier et al., 1997), as well as consequences for water column biogeochemistry (Souchu et al., 2001). On the other hand, causative factors of coastal eutrophication, such as increased nitrogen and phosphorus loading, may by virtue of higher primary production be associated with enhanced shellfish growth (Weiss et al., 2002).

This paper presents a modelling approach for the analysis of farm-scale aquaculture, applicable to a range of widely cultivated shellfish species. The Farm Aquaculture Resource Management (FARM) model is targeted at farmers and managers. Whilst distilled from more complex models, FARM has therefore been designed as a simplified screening model, using a reduced parameter set, based on data which are easily available. The main objectives of this work are:

(i) to develop a model for determining sustainable carrying capacity in shellfish aquaculture farms;
(ii) to optimise culture practice, such as timing and sizes for seeding and harvesting, densities and spatial distributions, both in terms of total production and economic returns;
(iii) to assess the role of shellfish farms in eutrophication control and emissions trading.

2. Methods

2.1. Conceptualisation

The FARM model simulates processes at the farm scale (about 100–1000 m), considering advective water flow and the corresponding transport of relevant water properties. These properties include the total concentration of suspended particulate matter (TPM), separate components of that suspended food resource which include living phytoplankton organics as distinct from all remaining "detrital" organics, and dissolved materials which include ammonia and dissolved oxygen (DO). The general layout for the model is shown in Fig. 1, and is applicable to suspended culture from rafts or longlines as well as to bottom culture. Horizontal water transport is simulated using a one-dimensional model, following e.g. Bacher et al. (2003), to which vertical transport is added for suspended culture.

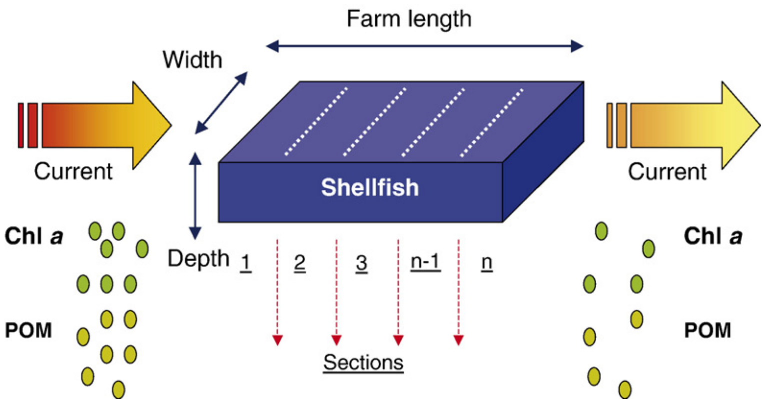

Fig. 1. Farm layout (rope and bottom culture).

Requirements for input data have been reduced to a minimum, since the model is aimed at the shellfish farming community and local managers in different parts of the world. Model inputs may be grouped into data on (i) farm layout, dimensions, species composition and stocking densities; (ii) suspended food entering the farm; and (iii) environmental parameters.

FARM integrates a combination of physical and biogeochemical models, shellfish growth models and screening models for determining production and for eutrophication assessment. These components are illustrated in Fig. 2 and described in detail below.

2.2. Physical and biogeochemical models

The general formulation used in FARM for modelling pelagic state variables in a suspended culture system is given in Eq. (1):

$$\frac{\partial C}{\partial t} = -u\frac{\partial C}{\partial x} - w\frac{\partial C}{\partial z} + f(C, \sum_{i=1}^{i=m} n_i \gamma_i) \tag{1}$$

where:

C concentration of resource (phytoplankton, POM, TPM)

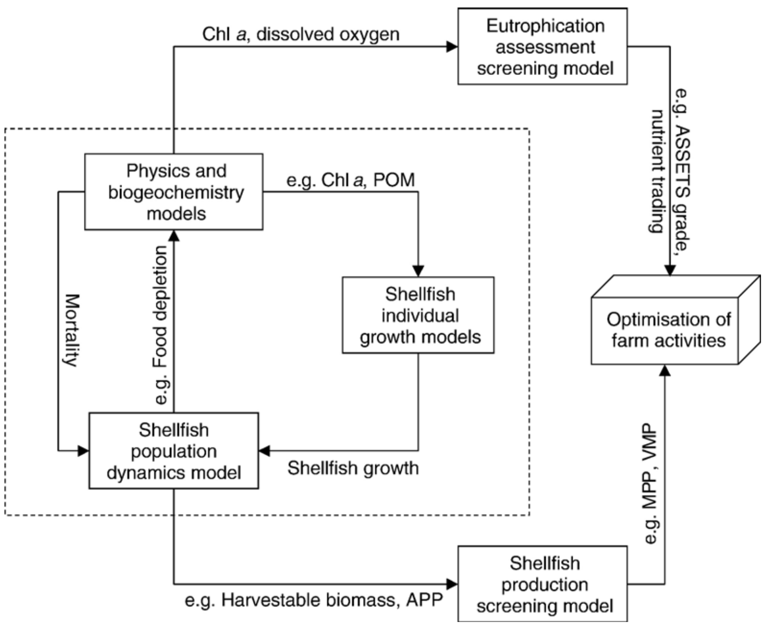

Fig. 2. Conceptual scheme of the various components of the FARM model. The model core is within the dotted rectangle, the two screening models are external.

t	time
u	mean horizontal water velocity normal to farm cross-section
x	farm section length
w	fall velocity of suspended particles
z	farm section depth
m	number of weight classes in the population
n_i	number of cultivated shellfish in weight class i
γ_i	growth functions for individual shellfish in weight class i

A mean unidirectional horizontal flow is considered, based on the current speed and on the farm dimensions, which may be defined as a series of contiguous sections or boxes, both to allow the analysis of different culture layouts and to minimise numerical errors. The model is designed to be applied over a time-scale which encompasses the range of cultivation periods observed in shellfish aquaculture, which may range from a few months to 2–3 years. Given the restriction imposed by the spatial scale of simulations for small farms, the specification of a high number of sections conditions the model time step, which is automatically determined to satisfy the Courant condition for stability.

Vertical fluxes for particulates are calculated for farms that implement suspended culture. At every time step, FARM calculates the dynamic viscosity based on the water temperature and salinity, and uses the Stokes equation to determine the fall velocity and particle deposition, taking different grain sizes into account following Ferreira et al. (1998). For farms implementing bottom or near-bottom culture involving benthic dredging or trestle systems, the deposition term is not considered.

The third term in Eq. (1) is a general representation of sinks and sources associated to shellfish growth — this term may be a sink for e.g. dissolved oxygen or chlorophyll *a*, a source for e.g. excreted ammonia, or both for e.g. POM and other particulate matter, which may be removed during ingestion and returned to the system as pseudofaeces and faeces.

2.3. Shellfish models

The growth of five different bivalve species is simulated in FARM (Table 1). Different types of models have been used, but all have in common the simulation of individual growth. The models for clams (Solidoro et al., 2000), Chinese scallop (Hawkins et al., 2002) and cockles (Rueda et al., 2005) are fully described in the literature. The models for mussels and oysters build upon that described for the Chinese scallop (Hawkins et al., 2002), and which has since been developed into a generic model structure for the dynamic simulation of feeding, metabolism and growth in different species of suspension-feeding bivalve shellfish, calibrated and validated for these and other species cultured at contrasting sites throughout Europe (Hawkins et al., in preparation).

Table 1
Shellfish species and models used in FARM

Species	Common name	Reference/model	Model type
Crassostrea gigas	Pacific oyster	Hawkins et al. (in preparation); ShellSIM	Ecophysiological
Mytilus edulis	Blue mussel	Hawkins et al. (in preparation); ShellSIM	Ecophysiological
Tapes phillipinarum	Manila clam	Solidoro et al. (2000)	Bioenergetic
Chlamys farreri	Chinese scallop	Hawkins et al. (2002)	Ecophysiological
Cerastoderma edule	Cockle	Rueda et al. (2005); COCO	Ecophysiological

To simulate the biomass production of market-size organisms, each model of shellfish growth is integrated in a population dynamics framework using well-established equations (e.g. Nunes et al., 2003; Nobre et al., 2005). Growth rates for individual shellfish are calculated on the basis of food supply and environmental parameters supplied by the physical and biogeochemical models. Shellfish mortality is also required as a driver for the population dynamics model. Average natural mortalities were estimated from data describing cultivation practices in Europe and China, and which are implemented in FARM (Fig. 2) according to established environmental stressors that include high temperatures, low salinities and low concentrations of dissolved oxygen (Hawkins and Bayne, 1992).

2.4. Screening models

Two types of screening models were incorporated in FARM. These are described below:

2.4.1. Aquaculture production

The outputs of the FARM model enable a detailed analysis of the production of market-sized animals for each cultivated species. Multiple simulations with increasing shellfish density yield a curve representing the total physical product (TPP) in tons total fresh weight (TFW). This is a Cobb–Douglas production function (e.g. McCausland et al., 2006) of the form given in Eq. (2):

$$Y = f(x_1, |x_2, x_3, \ldots x_n) \tag{2}$$

where:

Y	output of harvestable shellfish
x_1	initial stocking density of seed, considered the only variable input
$x_2 - x_n$	other inputs, considered to be held constant

The model calculates the average physical production (APP) after each run (Eq. (3)):

$$\mathrm{APP}x_1 = \frac{\mathrm{TPP}}{x_1} \tag{3}$$

and the first-order derivative of the production function provides the marginal physical product (MPP). For constant input unit cost P_x and output unit price P_y, the farmer's profit will be maximised when the value of the marginal product (VMP) equals P_x, VMP may be defined as:

$$\mathrm{VMP} = \mathrm{MPP} \cdot P_y = P_x \tag{4}$$

making it possible to determine the MPP for profit maximisation according to Jolly and Clonts (1993). The validity of this approach, which is based on marginal principles, additionally assumes that (i) inputs are unlimited, (ii) input purchases and output sales are made in a perfectly competitive market situation, (iii) the farm is a small production system which sells only this product, and (iv) seed is the only variable input, such that lease, labour etc. are fixed costs.

The FARM model also calculates the equivalent APP expressed as individuals, providing an indicator of the capacity of the farm to produce harvestable animals.

2.4.2. Eutrophication assessment

To evaluate the effects of a shellfish farm with respect to eutrophication, the Assessment of Estuarine Trophic Status (ASSETS) model (Bricker et al., 2003) was adapted for use at the local scale. This model, which extends the US National Eutrophication Assessment (NEEA) methodology (Bricker et al., 1999), has been applied at the system scale in many estuaries and coastal bays in the US, EU and Asia (e.g. Nobre et al., 2005; Ferreira et al., 2007; NOAA/IMAR, 2006).

With reference to the ASSETS model, the farming of filter-feeding bivalves in suspended culture may have positive impacts by reducing primary symptoms of eutrophication such as elevated chlorophyll *a* (e.g. Newell, 2004), with an associated favourable effect on the secondary symptom dissolved oxygen, although the shellfish are themselves a sink for DO. In parallel, the removal of TPM and POM due to feeding, and the consolidation of suspended particles into larger (up to 40×) and more rapidly sedimenting composites as faeces and pseudofaeces (e.g. Giles and Pilditch, 2004; Newell, 2004), may promote increased water clarity, leading to a recovery in submerged aquatic vegetation (SAV). Chl *a*, macroalgae, SAV loss, DO and harmful algae are the eutrophication symptoms considered in the ASSETS determination of *State* (Overall Eutrophic Condition — OEC). In the present FARM model, only Chl *a* and DO are considered, and aspects of the assessment related to weighting of spatial coverage and frequency of occurrence are not included. Conceptually, the various farm sections are equivalent to the ASSETS salinity zones, and the level of expression (S_l) values for Chl *a* and DO are obtained by integration over the total farm area, using Eqs. (5) and (6) respectively.

$$S_l = \sum_{1}^{n} \left(\frac{A_s}{A_f} E_l \right) \tag{5}$$

where:

A_s	surface area of farm section
A_f	total farm surface area
E_l	expression value in each section
n	number of farm sections

and

$$S_l = \max \left(\overset{n}{\underset{1}{E_l}} \right) \tag{6}$$

Eq. (6) selects the highest level of expression of the ASSETS secondary symptom DO, in keeping with the precautionary nature of the assessment method. The standard OEC decision matrix (Bricker et al., 2003) is used to derive the final grade for *State*. The *Pressure* and *Response* components within ASSETS are not applicable at the farm scale.

2.5. Implementation, validation and sensitivity analysis

2.5.1. Implementation

FARM has been implemented as a client–server application, using an object-oriented approach, and is available at http://www.farmscale.org/. The model interface is illustrated in Fig. 3, and allows the user to:

(i) define farm dimensions, types and durations of cultivation;
(ii) define environmental variables (e.g. Chl *a*, POM, TPM, O_2);
(iii) select species and culture densities.

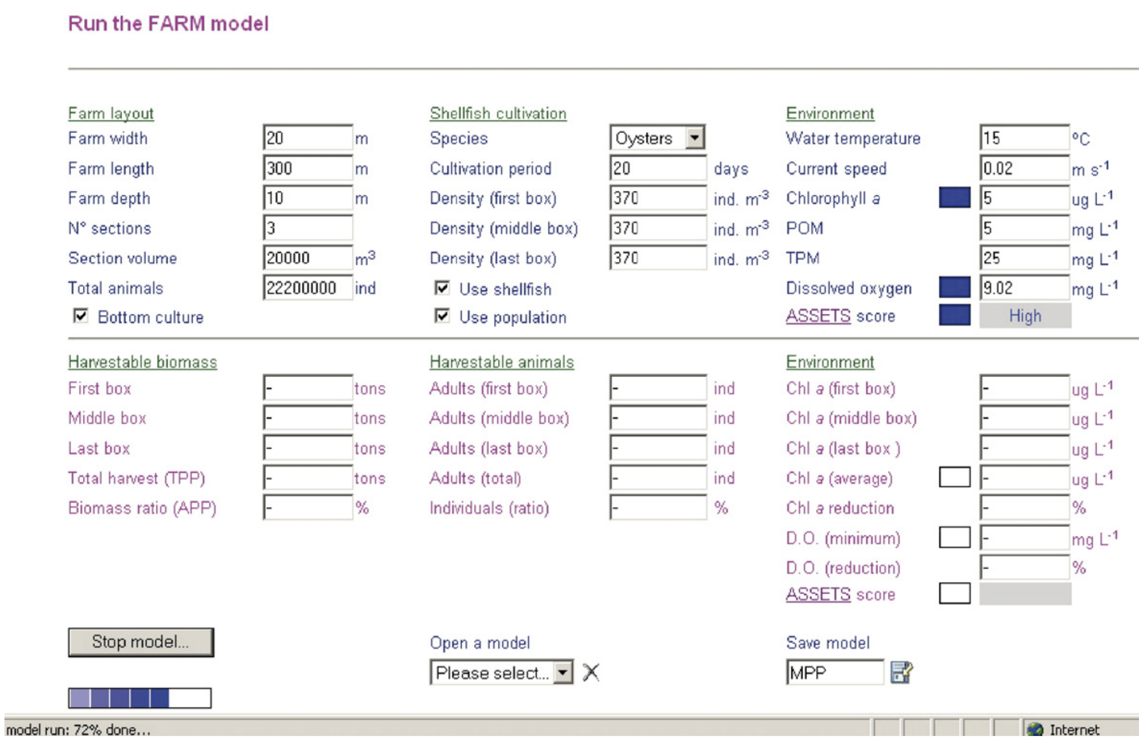

Fig. 3. FARM screenshot.

Inputs for environmental variables may be derived from field data or from larger scale models. If a value is not entered for dissolved oxygen, the model automatically calculates it as 100% dissolved oxygen saturation based on temperature and salinity (after Benson and Krause, 1984).

2.5.2. Validation

Various parts of the FARM model were developed and tested in PowerSim™, Stella™, C++ and FORTRAN. Each of the individual shellfish growth models has been validated under culture conditions (refer above and Table 1). Many of the functions used in FARM have been previously used in studies of system-scale carrying capacity, validated for systems in Europe (Ferreira et al., 1998; Nobre et al., 2005) and China (Nunes et al., 2003). Nunes et al. (ibid) calculated a bay-wide production of about 45,000 TFW during the first year that the Chinese scallop *Chlamys farreri* was cultivated in Sanggou Bay, N.E. China; later years have superimposed annual cohorts, resulting in larger harvests (6 year mean = 59,868 TFW y^{-1}). FARM was run for a 1 ha (500 m × 20 m) farm using identical seed densities and the results scaled up to 34 km^2, which is the total cultivation area in Sanggou Bay. The scaled-up TPP was 42,160 TFW y^{-1}, representing about 94% of the system-scale model results, and which appears acceptable. FARM is expected to predict lower yields due to depletion effects, since ecosystem-scale models calculate carrying capacity within larger boxes, potentially neglecting resource scarcity at the farm-scale.

2.5.3. Sensitivity analysis

The publicly available version of FARM presently uses constant user-defined forcing for water temperature, Chl *a*, POM and TPM. In nature, all of these vary seasonally. Therefore, time-series data (Fig. 4) available

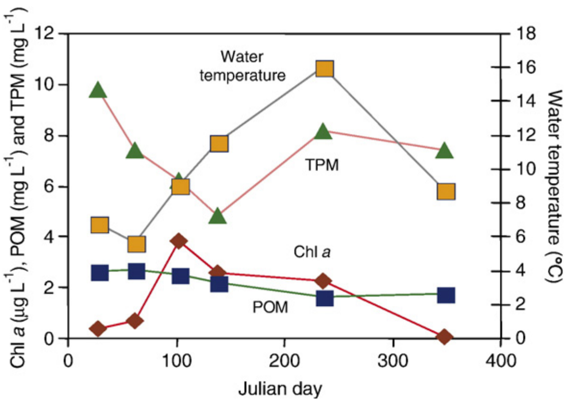

Fig. 4. Time series for sensitivity analysis to constant or variable environmental forcing. Data were collected as part of the SMILE project (IMAR/PML/CSIR/DARDNI, 2006).

Table 2
Sensitivity analysis to annual cycle of chlorophyll *a*, POM, TPM and water temperature*

Species	Model output	Constant (average) values	Step interpolation	Linear interpolation
Mussels	TPP (tons TFW)	45.2	54.4	46.2
	APP	3.01	3.62	3.08
	% Adults	60	72	62
	Chl *a* (μg L^{-1})	1.47	0.26	2.16
	DO (mg L^{-1})	8.96	8.93	8.95
	ASSETS grade	High	High	High
Oysters	TPP (tons TFW)	54.3	60.8	56.2
	APP	3.62	4.05	3.75
	% Adults	72	81	75
	Chl *a* (μg L^{-1})	1.32	0.14	1.91
	DO (mg L^{-1})	8.9	8.86	8.9
	ASSETS grade	High	High	High

*Model runs: suspended culture for 210 days, 50 animals m^{-3}, current speed = 0.02 m s^{-1}. For constant values: water temperature = 9.64 °C; Chl *a* = 1.63 μg L^{-1}; POM = 2.25 mg L^{-1}; TPM = 7. 31 mg L^{-1}; for interpolation data points see Fig. 4.

for northern Irish sea loughs (IMAR/PML/CSIR/DARDNI, 2006) were used to force the model to explore the sensitivity of outputs to variable inputs, over a 210 day cultivation period.

The model outputs for three different cases are shown in Table 2, for culture of both the blue mussel and Pacific oyster. For the runs with constant forcing we used the annually averaged data, and additionally tested using stepwise and linear interpolation of the data series.

There were small differences in almost all the outputs when the three forcing approaches are compared. However, the maximum difference in TPP between runs using average values and linear interpolation was no more than 3%. Larger differences of up to 20% in mussels and 12% in oysters were observed between step interpolation and both the average and linear runs. This was probably because step interpolation forces plateaus of high or low values over long periods, which will have pronounced effects on production, particularly during periods such as the spring bloom (Fig. 4), when there are steep gradients in the chlorophyll data. An ANOVA for the three data sets indicates that the results for TPP, APP, % adults, Chl *a* and DO are indistinguishable, with $F = 0.028$ ($P < 0.97$) for mussels and $F = 0.009$ ($P < 0.99$) for oysters (critical F value for $P < 0.05$ is > 3.88).

Further tests were also carried out by comparing outputs for mussels and oysters using the averaged and linearly interpolated data for 5 different current speeds, ranging from 0.01 m s^{-1} to 0.5 m s^{-1}. All other input data were as in the previous example. An ANOVA applied to the output pairs also suggests that statistical differences are not significant for either mussels ($F = 0.04$) or oysters ($F = 0.05$, $P_{<0.1} \geq 3.46$ for both species). Finally, similar tests were carried out using the average of data collected at seven sampling stations monthly over one year from 1999 to 2000 in Sanggou Bay, China, as described for the SPEAR project at http://www.biaoqiang.org/. For the Chinese scallop *Chlamys farreri*, comparisons showed that TPP and APP were identical using averaged and linearly interpolated environmental forcing.

Overall, the comparisons for averaged and time-varying data suggest that outputs using constant forcing are sufficiently accurate for the purposes of this type of screening model.

3. Results and discussion

A series of potential applications of the FARM model are reviewed below. These include: (i) prospective analyses of culture location and species selection; (ii) optimisation of culture practice, including effects of the times of seeding and harvesting, shellfish densities and spatial distributions on both the total production and economic returns; and (iii) environmental assessment of farm-related eutrophication effects (including mitigation). The example case studies reported have been prepared using realistic model input data drawn from a variety of cultivated coastal systems. The stocking densities selected fall within the ranges cited by Bacher et al. (2003).

3.1. Example applications

3.1.1. Farm location

Table 3 shows an example for three potential farm locations, considering areas with fast (0.5 m s^{-1}), medium (0.1 m s^{-1}) and slow (0.02 m s^{-1}) current speeds. All other environmental variables and initial stocking density are kept constant. The model was applied for bottom culture of the oyster *C. gigas* over a short cultivation period of 45 days. Modelled responses for TPP (simulated as TFW), APP and final mean Chl *a* are hyperbolic, and at slow current speeds show greater food depletion and less efficient production, reflected in an APP which is 50% lower than at other siting scenarios.

Table 3
Culture siting for *C. gigas* (bottom culture) at locations with different current speeds (above the dotted line: initial conditions, with scenario changes underlined; below the line: model outputs)

Farm	Dimensions (m)	Species	Model
	300 x 20 x 10	*C. gigas*	ShellSIM
Cultivation period (d)	45	45	45
	Chl *a* (μ g L^{-1})	POM (mg L^{-1})	TPM (mg L^{-1})
Food	10	5	25
Environment	Density (ind m^{-3})	*T* (°C)	O_2 (mg L^{-1})
Sections 1, 2, 3	500, 500, 500	15	8.7
Current speed	High	Medium	Slow
(m s^{-1})	0.5	0.1	0.02
Total seed ($x10^3$ ind)	30, 000	30, 000	30, 000
Total harvest (tons TFW)	727.1	692.4	323.9
Biomass ratio (APP)	4.85	4.62	2.16
Final mean Chl *a* (μg L^{-1})	7.9	4.7	2.1
Final min. O_2 (mg L^{-1})	8.4	7.7	6.9
Income (k)	3656	3462	1619

There is no significant difference in the production simulated at sites with fast and medium current speeds, but the latter have an environmental advantage with respect to Chl *a* reduction. That advantage may, however, be offset by an increase in local shellfish biodeposit production. Those deposits will have a smaller albeit more concentrated benthic footprint, since there will be lower particle dispersion at medium current speeds: 0.5 m s^{-1} is often considered a threshold between depositional and dispersive areas. It is important to bear in mind, however, that advective components transversal to the main flow direction are neglected in the present version of the FARM model. This approximation is reasonable both with respect to siting criteria for shellfish farms, which include the prevailing water currents, and in order to retain the simplicity of input data. However, the contribution of perpendicular flow components and of turbulent diffusion may be relevant — our model may thus underestimate resource renewal, and thus carrying capacity in absolute terms, though the relative effects of alterations in forcing functions are likely to remain unchanged.

3.1.2. Culture layout

The relative densities of shellfish in different sections of each farm may also condition the overall production. Distribution scenarios for (a) increasing density; (b) equal density; and (c) decreasing density, together with simulated consequences, are shown over three farm sections in Table 4.

Comparisons were carried out over a 45 day period, as an example of ongrowing during optimal time of year, with a nominal current speed of 10 cm s^{-1}, for a standard total seed stock of 18×10^6 blue mussels in suspended culture, distributed over 9 farm sections. The number of modelled sections was increased from 3 to 9 to reduce the potential for numerical artifacts that might influence the results.

Predictions from this example indicate that higher seed densities in the first sections of the farm result in

Table 4
Culture distribution for *M. edulis* in suspended culture with different layouts (above the dotted line: initial conditions, with scenario changes underlined; below the line: model outputs)

Farm	Dimensions (m)	Species	Model
	300 x 20 x 10	*M. edulis*	ShellSIM
Cultivation period (d)	45	45	45
Food	Chl *a* (μg L^{-1})	POM (mg L^{-1})	TPM (mg L^{-1})
	6	2	25
Environment	Current speed (m s^{-1})	*T* (°C)	O_2 (mg L^{-1})
	0.1	15	8.7
Distribution scenario	Increasing	Equal	Decreasing
Density (ind m^{-3})	200, 300, 400	300 (all)	400, 300, 200
(9) Sections 1-3, 4-6, 7-9			
Total seed (x 10^3 ind)	18, 000	18, 000	18, 000
Total harvest (tons TFW)	64.7	82.8	100.3
Biomass ratio (APP)	0.72	0.92	1.11
Final mean Chl *a* (μg L^{-1})	5.3	5.1	4.9
Income (k€)	323.5	414	501.5

significantly higher overall production. If growth were a simple function of food concentration, then as long as the overall biomass of seed were the same, longitudinal variations in stocking density would not lead to changes in production. However, additional release of POM from pseudofaeces and faeces produced by shellfish in upstream sections of a farm constitutes an extra source of food for animals in downstream sections (Newell, 2004). Alternatively, and consistent with our observation of higher overall production given higher seed densities in the first sections of the farm, then because individual growth is simulated by means of non-linear functions whereby ingestion rates and growth may become saturated above "optimal" food concentrations which differ between species (e.g. Hawkins et al., 2002), low seed densities and thus with lower food depletion may not maximize growth. Similarly, at lower seed densities, a greater proportion of animals will reach the largest weight classes, and which have a much lower growth efficiency (=energy deposited as growth/energy absorbed) (Nunes et al., 2003). Whilst these factors may result in better yields with increasing densities, interrelations with current speed are all-important. For example, a 20 day model run for oyster bottom culture using slow current speeds of 1 cm s^{-1} results in severe food depletion, with no growth in downstream sections

Table 5
C. gigas in bottom culture with different stocking densities (above the dotted line: initial conditions, with scenario changes underlined; below the line: model outputs)

Farm	Dimensions (m)	Species	Model
	300 x 20 x 10	*C. gigas*	ShellSIM
Cultivation period (d)	180	180	180
	Chl *a* (μg L^{-1})	POM (mg L^{-1})	TPM (mg L^{-1})
Food	5	5	25
Environment	Current speed (m s^{-1})	*T* (°C)	O_2 (mg L^{-1})
	0.02	15	8.7
Cultivation scenario	Low	Medium	High
Density (ind m^{-3}) Sections 1, 2, 3	25 (all)	100 (all)	500 (all)
Total seed (x 10^3 ind)	1500	6000	30, 000
Total harvest (tons TFW)	34.3	137.3	400.2
Biomass ratio (APP)	4.58	4.58	2.67
Final mean Chl *a* (μg L^{-1})	4.3	2.8	0.9
Income (k)	171.5	686.5	2001

Table 6
Production and economic parameters for different seeding densities

Seed (tons)	TPP (tons)	APP	MPP	VMP (€)	Total revenue (k€)	Total cost (k€)	Profit (k€)
0	0	0.00	0.00	0.0	0	0	0
7.5	15	1.98	1.98	9.9	74	6	69
15	31	2.05	2.12	10.6	154	11	143
30	66	2.20	2.34	11.7	329	23	307
39	86	2.21	2.23	11.2	430	29	401
60	118	1.97	1.53	7.7	591	45	546
75	128	1.71	0.68	3.4	642	56	586
86	131	1.54	0.30	1.5	657	64	593
90	***132***	1.47	**0.15**	0.8	661	68	**593**
99	133	1.34	0.07	0.3	664	74	590
111	133	1.19	−0.02	−0.1	663	83	580
120	132	1.10	−0.07	−0.3	660	90	570
150	129	0.86	−0.10	−0.5	645	113	532
180	125	0.70	−0.12	−0.6	627	135	492

Optimal values shown in bold.

of the farm, such that a 14% increase in yield is instead predicted for a cultivation layout with increasing downstream density.

3.1.3. Stocking density and production screening model

Table 5 shows results for bottom culture of Pacific oyster cultivated for 180 days at three different densities.

At the low and medium densities of 25 and 100 animals m^{-3}, respectively, the APP remains constant at 4.6. However, at the high density of 500 animals m^{-3}, APP reduces to 2.7. Although the TPP increases from 34 tons TFW to 400 tons TFW at the highest density, the farm becomes progressively less profitable.

To obtain a production function for TPP, this simulation was extended over a range of seeding effort from 0 to 180 tons, and the results presented in Table 6. An analysis of the interactions of the resulting TPP, APP and MPP curves shows that these can be divided into three stages (Fig. 5). In Stage I, the MPP curve is above APP, and crosses it when the derivative of APP becomes negative.

The farmer should clearly consider increasing inputs (in this case seeding density) while the APP is still increasing. Stage III begins when MPP=0. Thereafter, TPP decreases despite increased seed input, which is clearly undesirable on a financial basis. Stage II is the region where profit is maximised. The point at which profit maximisation occurs was determined in this example by applying Eq. (4) with P_x=0.75€ and P_y=5€, giving an MPP=0.15 and optimum seed input of 90 tons TFW (density of 300 animals m^{-3}).

The maximum biological production (TPP) occurs when MPP=0, and corresponds to a seed input of about 100 tons TFW. However, maximising biological production does not maximise profits, which are greatest at lower

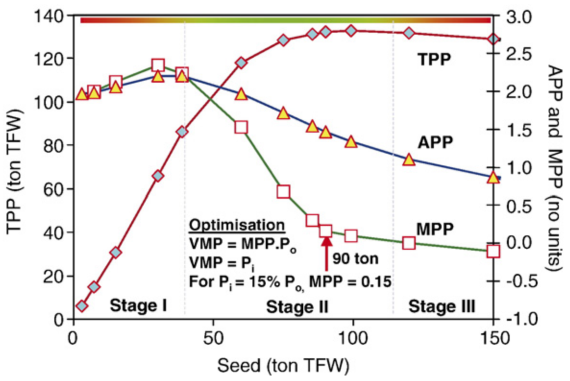

Fig. 5. Economic analysis. Simulations carried out with *C. gigas*, 20 day cultivation period, 5 μg L^{-1} Chl *a*.

levels of input and output than those that maximise production. The profit maximising rule is based on marginal principles. Therefore, a producer who bases production decisions on average or total production and revenue principles will earn less profit than one who uses marginal analysis (Jolly and Clonts, 1993). The level of fixed cost does not influence the decision of a producer on optimal use of the variable input, since this is based on the comparison of values of Marginal Product and Marginal Input. Multiple input and output variables such as may occur under multi-species culture may also be considered by using marginal analysis, or alternative methods may be applied (e.g. Sharma et al., 1999).

FARM allows modelling of multi-species culture for different combinations of bivalves. A number of simulations with a two-species mix using various ratios of oysters and mussels did not show enhanced TPP or APP, both for constant and variable forcing. However, different species of filter-feeding shellfish feed upon different components of the suspended seston, with different maximal rates, and which occur at different seston concentrations (e.g. Hawkins and Bayne, 1992). For these reasons, it is to be expected that species composition will affect total productivity. For example, Duarte et al. (2003) simulated the means by which total production of shellfish could be significantly increased through spatial separation of standard seeding quantities for oysters and scallops cultured coincidentally within Sanggou Bay, China; and which appeared to result from reduced inter-specific competition. Further to which, regardless of enhancements in production alone, there may be economic advantages in combining slower-growing, higher-value species with more productive but commercially less interesting ones.

3.1.4. Eutrophication control and emissions trading

Our final example provides an analysis of the interactions between shellfish culture and coastal eutrophication (Table 7). Bivalve growth was simulated over a 45 day cultivation period at three different seed densities of 25, 100 and 500 individuals m^{-3}. As before, increasing seed density improves the final yield

Table 7
Environmental assessment — the ASSETS model (above the dotted line: initial conditions, with scenario changes underlined; below the line: model outputs)

Farm	Dimensions (m)	Species	Cultivation (d)
	300 x 20 x 10	Generic	45
Food	Chl *a* (μg L^{-1})	POM (mg L^{-1})	TPM (mg L^{-1})
	11	5	25
Environment	Current speed (m s^{-1})	*T* (°C)	O_2 (mg L^{-1})
	0.02	15	7.0
Cultivation scenario	Low	Medium	High
Density (ind m^{-3})	25 (all)	100 (all)	500 (all)
Sections 1, 2, 3			
Total seed (x 10^3 ind)	1500	6000	30, 000
Total harvest (tons TFW)	13.1	36.8	39.1
Final mean Chl *a* (μg L^{-1})	9.5	6.0	1.3
Final minimum O_2 (mg L^{-1})	5.9	3.8	1.8
ASSETS score	Good	Moderate	Poor
Income (k€)	65.5	184	195

(although APP is lower), but the interaction between cultivation and the ASSETS eutrophication indicators introduces an additional "sustainability" metric for carrying capacity assessment.

As expected, the farm with lowest shellfish density shows the lowest food depletion, where Chl *a* is only reduced by about 15%. However, DO does not fall below 6 mg L^{-1}, resulting in an overall ASSETS score of *Good*. Alternatively, the increase in density progressively leads to improved water quality as regards Chl *a*, but the increase in shellfish population metabolism leads to severe reductions in DO. The ASSETS grade correspondingly shifts with increasing cultivation intensity from *Moderate* at medium shellfish density to *Poor* at high shellfish density. At the highest density of 500 individuals m^{-3}, the farm area is classified as hypoxic, both using the ASSETS range (0–2 mg L^{-1}) and the threshold of <2.8 mg L^{-1} suggested by Altieri and Witman (2006). Hypoxia is responsible for severe bivalve mortality, linked both to nutrient-related eutrophication symptoms and to benthic community respiration (e.g. Altieri and Witman, 2006). FARM allows a user to test for thresholds of low oxygen and to examine potential consequences for water quality and stock mortality.

Regulatory pressure on coastal water quality standards has matched expansion pressure on shellfish aquaculture, particularly in the EU with the enactment of the Water Framework Directive (European Commission, 2000) and the proposed Marine Strategy Directive. The US Clean Water Act (CWA, 1972) and other policy initiatives (e.g. USEPA, 2001) have also sharpened the focus on related issues. Shellfish aquaculture is widely considered to have a positive impact, given production near the base of the trophic chain (e.g. Naylor et al., 2000) and potential enhancements both of primary production and biodiversity (Gibbs, 2004; McKindsey et al., 2006). However, the environmental role of shellfish farms with respect to the control of nutrient emissions has not to our knowledge been quantitatively addressed. To assess the role of cultured shellfish on nutrient removal by means of a mass balance, FARM was run for bottom culture of oysters over a 180 day period. Fig. 6 displays the results for nitrogen, which show a net removal of about 10.7 tons y^{-1}. A similar calculation can be carried out for phosphorus. The filtration and hence removal of particulate organic nitrogen (PON) and other organic matter by shellfish is offset by additions due to ammonia excretion and faeces. Pseudofaeces have not been included in this balance because they are rejected prior to ingestion of phytoplankton and detritus. Whilst phytoplankton primary production directly removes dissolved available inorganic nitrogen (DAIN) from the water column, the PON present in suspended particulates may originate from a variety of sources: these include DAIN incorporated in plant detritus, PON from land discharges, faecal material, carcasses etc. (e.g. Canuel and Zimmerman, 1999; Goñi et al., 2003).

Our mass balance indicates that 40% of ingested nitrogen was returned to the system due to shellfish excretion and elimination, which is not inconsistent with values of up to 73% reported by Hawkins and Bayne (1985).

If a standard population-equivalent (PEQ) of 3.3 kg $person^{-1}$ y^{-1} is considered, the net nitrogen removal

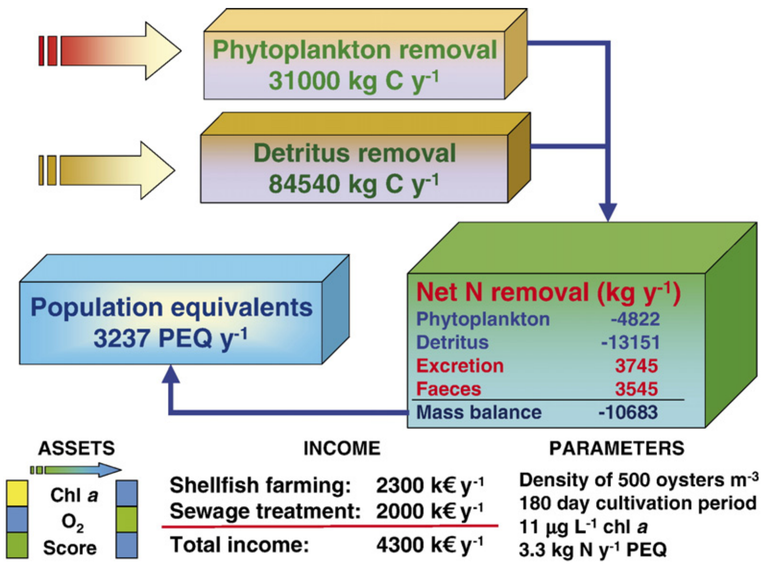

Fig. 6. Mass balance and nutrient emissions trading.

from a 6000 m^2 farm corresponds to an untreated wastewater discharge from over 3000 PEQ, or the treated sewage from about 18,000 PEQ. Sewage treatment costs per inhabitant are highly variable (Galvão et al., 2005) — for the untreated scenario, considering an average unit treatment cost of about 650€, the substitution value of the shellfish farm as regards nutrient removal is 2000 k€ y^{-1}, almost 50% of the combined total annual value of the farm operation. Emissions trading, which is well developed for carbon in the context of global change (e.g. Klaassen et al., 2005; Böhringer et al., 2006; Soleille, 2006), is in its infancy as regards nitrogen and phosphorus discharges to the coastal zone (Schwabe, 2000; Nishizawa, 2003; Luo et al., 2005). The USEPA has prepared a guidance document on this topic (Boyd et al., 2004), which proposes nutrient trading guidelines using the watershed as a core unit. Tools such as the FARM model will contribute to the assessment and valuation of potential trading partners. In the US and northern Europe, reduction of emissions to the coastal zone is now primarily focused on agriculture (Ribaudo et al., 2001; Boesch, 2006). One option open to agriculture and other activities discharging nutrients to the coastal zone is the purchase of nitrogen or phosphorus credits from sectors such as bivalve aquaculture which are nutrient sinks.

4. Conclusion

The model presented in this paper has a range of potential applications for farm-scale assessment of coastal and offshore shellfish aquaculture. Since FARM is a model directed both at the farmer and the regulator, the required inputs have been deliberately reduced to encourage usability. The integration of biological, production and economic functions with ASSETS, allowing eutrophication assessment using a subset of primary and secondary symptoms, means that FARM is effectively a screening model for shellfish productivity, economics and water quality. Growing emphasis on sustainability means that these components can no longer be dissociated. The model's simple interface hides complex internal processing, including transport equations, shellfish individual growth, population dynamics, dissolved oxygen balance, nitrogen mass balance, production functions and eutrophication assessment. Care must of course be taken in the application of FARM, as with any model, given the approximations that have been made. In particular (i) the model forcing is considered to be constant; (ii) turbulent mixing is not included; and (iii) there are a number of processes, such as fouling or predation, which are not presently simulated. An option for time-varying forcing will be added in the future, together with a component for harvesting, thereby allowing a more realistic assessment of farm-scale carrying capacity by incorporating the removal of harvestable animals. The trade-off for increased realism is a greater requirement for input data and a potential reduction in usability.

The FARM model is part of the rapidly emerging paradigm of Software as a Service (SaaS — e.g. Currie, 2003). The implementation of ecological models as client–server software on the world wide web greatly improves accessibility, encourages user feedback and helps to bridge the "digital divide" (e.g. Brooks et al., 2005). The development and implementation of this kind of model is typically supported by research grants, but maintenance (the key software issue) – and typically unsupported by research grants – is far easier (and therefore cheaper) if all clients are simultaneously able to run an updated model from a server, rather than downloading client-specific upgrades. The FARM model is publicly available at http://www.farmscale.org/.

Since the papers by Tenore et al. (1973) and Ryther et al. (1975) were published over 30 years ago, a body of literature has accumulated on the potential of IMTA for enhanced production. FARM will be developed in 2007 to include options for including fish cages and seaweeds, based on work in progress in China (Ferreira et al., 2006), and drawing on previous models for fish culture (e.g. Stigebrandt et al., 2004). These developments will not, however, compromise the simplicity of FARM's interface, to facilitate use by farmers and managers.

Assessment of carrying capacity at the farm scale should ideally integrate all four components (i.e. physical, production, ecological and social elements), to help ensure that: (i) space, production, revenue and profit are adequate for a viable business; (ii) the ecological consequences of production are acceptable by both the community and by regulators, taking into account potential benefits, particularly as regards nutrient emissions from agriculture; and (iii) social benefits are clearly recognized — in some areas such as the west of Scotland or the maritime provinces in eastern Canada this may be one of the few sustainable options for the survival of rural communities.

Coastal eutrophication is identified as an issue worldwide (e.g. Tett et al., 2003; Paerl, 2006), leading to increased awareness of the need for holistic management of nutrient emissions, with an emphasis upon nitrogen. As a result, natural and social sciences are belatedly working together (e.g. Byström et al., 2000; Erisman et al., 2001; Gren and Folmer, 2003; Atkins and Burdon, 2006) to help promote integrated solutions.

Shellfish aquaculture plays a significant role in eutrophication control throughout many coastal areas in S.E. Asia, although this has probably developed more as a by-product of the need to use the lower tiers of the food chain to help feed the population. FARM represents a contribution to the quantitative assessment of bivalve culture in eutrophication control, and can play a part in developing an economically meaningful nutrient emission trading policy for coastal areas.

Acknowledgements

Financial support from EU contracts INCO-CT-2004-510706 (SPEAR) and 006540 (SSP8) (ECASA) for parts of this work is gratefully acknowledged. The authors thank R. Pastres for making available the computer code for the T. phillipinarum model, and three anonymous referees for their constructive comments in helping to significantly improve this manuscript.

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