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Analysis

A dynamic ecological–economic modeling approach for aquaculture management

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ABSTRACT

This paper presents a Modeling Approach to Resource economics decision-maKing in EcoaquaculTure (MARKET model). The MARKET model was developed as a scenario-testing tool to provide insights on the ecological and economic interactions, which is a critical issue for sustainable aquaculture management. As a case study, the model was applied to simulate shellfish production in an embayment located in the East China Sea. A set of scenarios was used to compare the model outputs with expected trends and to test its capability to simulate relevant management scenarios. The comparison of simulated scenarios indicates that the MARKET model outputs followed the expected trends regarding both standard economic theory for consumption and production, and ecological economic theory. In all the scenarios we tested the area available for aquaculture was found to impose a limitation on production before it became less profitable to expand production. As such, in this case study, the production in the long run does not meet increasing demand. Reduction of the maximum cultivation area was simulated in one of the scenarios as an example of a conservation measure. As expected there was a reduction of the net profit of the farmers compared with the standard simulation. On the other hand, this scenario combined with an increase in price growth rate simulates a compensatory measure that led to a net profit in the same range as observed in the standard simulation. Overall the MARKET model provides insights and raises questions useful for the implementation of an ecosystem approach to aquaculture. Further developments include the simulation of waste generated by cultivated species in order to better support sustainable management objectives.

1. Introduction

Global consumption of finfish and shellfish as food has doubled since 1973. Evidence suggests that the large increase in the aquatic resources production in recent decades has resulted from the enormous growth in seafood demand in the developing countries (Delgado et al., 2003). China is the largest aquaculture producer in the world, with an average annual growth rate from 1980 to 2004 of 15% (Gíslason et al., 2006), and the only nation where farmed production exceeds wild catch (Sanchez et al., 2007). In 2006, 68% of total aquatic production in China was from aquaculture (FAO, 2009). The development of aquaculture in China has had a positive impact in terms of its contribution to nutrition, employment, and improvement in socio-economic status of both rural and urban communities (FAO, 2004). About 4. 3 million rural workers are directly employed in aquaculture with an annual per capita net income of 8667 Yuan (which converts to 1075 USD considering the exchange rate at the time of study, 1 USD = 8.06 Yuan) (FAO, 2005). Given the significance of aquaculture in China, changes in mariculture production due to changes in economic inputs or biophysical variability have a wider socio-economic impact on communities.

Just like any other food-producing sector in the world, aquaculture relies on renewable and non-renewable resources. Sustainable development and management of aquaculture thus requires an appropriate understanding of the conflicts and interactions between the resource use and its users. Such understanding contributes to improve governance in resource use, which is an important prerequisite of the sector's sustainability and one of the objectives of building an ecosystem approach to aquaculture (EAA) (Soto et al., 2008). Aquaculture is considered as the "solution" for bridging the supply and demand gap of aquatic food globally. There is however concern about the negative environmental impacts that some aquaculture practices can exert on coastal resources and ecosystems (Tovar et al., 2000; Xu et al., 2007).

The carrying capacity of the coastal ecosystem can represent a limit to the increase in aquaculture production. Depending on culture practices, this might be related to space limitations, availability of food resources or on the environmental capacity to assimilate aquaculture generated wastes (Sequeira et al., 2008). Apart from ecological limitations there are also economic cost limitations to production, illustrated through an analysis of the marginal cost in relation to marginal revenue (Gravelle and Rees, 1993). An economic analysis of

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aquaculture production must be based on realistic production cost and income projections that account for these economic limitations.

The focus of aquaculture management is often on maximizing the output and not the profit, which is not only economically inefficient, but carries unnecessary ecological risks. If the goals of sustainable aquaculture development are to be achieved, then there is need to understand both ecological and economic limitations. Aquaculture operations depend directly on the availability and quality of the marine resources and environment. If the marine ecosystem is overexploited the negative impacts will be felt in aquaculture farming operations and by all other downstream activities dependent on aquatic resources farming. This is particularly important for a country such as China that accounts for 68% of the world aquatic production, and where some of the marine ecosystems have a high percentage of reclaimed areas for aquaculture, e.g., 77% of the coastal usable area of Xiamen is occupied by aquaculture activities (Xue, 2005).

To ensure sustainable aquaculture production, it is crucial to understand the ecological and economic limits beyond which mariculture becomes less efficient. Dynamic modeling can provide a tool that facilitates the understanding of the complex feedbacks between ecological and economic aspects of aquaculture production. Resource managers and policymakers have come to understand that the sustainability of ecological and economic systems is tightly coupled (GESAMP, 2001). However, the complexity of the interactions may make informed resource decision-making extremely difficult, particularly given the dynamic nature of ecosystems and the difference in the scale of analysis of ecological and economic systems.

The integration between ecological and economic models is currently a developing discipline (Drechsler et al., 2007). Several conflicts were identified (Bockstael et al., 1995; Drechsler and Watzold, 2007) that explain the decoupling of these two disciplines, namely: (i) the scales of analysis; (ii) the communication/understanding between ecology and economics; and (iii) the implicit assumptions of each one.

In recent years there was an increase in the development of integrated ecological–economic models (Drechsler et al., 2007). According to Armstrong (2007), Bulte and van Kooten (1999) and Drechsler et al. (2007) these models tend to be less complex than the biological/ecological models alone. Jin et al. (2003) categorize ecological–economic models into 3 groups: (i) bioeconomic model approach; (ii) integration of complex environmental and economic models; and (iii) linear models, for instance the coupling of linear economic input–output model with a food web model.

This paper aims to develop a dynamic environmental and economic model as a tool for mariculture management and for EAA, and to illustrate a coupling approach. The main objectives are to:

1. Develop a conceptual model of the ecological–economic interactions in mariculture;
2. Implement a dynamic ecological–economic model in order to simulate (i) the socio-economic component of shellfish aquaculture production, (ii) its effects on the estuarine and coastal ecosystems, and (iii) feedbacks of the environmental system on the socio-economic system;
3. Simulate a set of scenarios to compare the model outputs with expected trends and to test its capability to simulate management scenarios.

2. Methodology

2.1. Conceptual approach

The Modeling Approach to Resource economics decision-maKing in EcoaquaculTure (MARKET) (Fig. 1), illustrates the major interactions which should be considered in mariculture between ecological and economic systems.

The MARKET model includes three components (Fig. 1): (i) the ecological component, which includes the relevant ecosystem biogeochemistry and the growth of aquatic resources; (ii) the economic component, which invests capital and labor for the production of the aquatic resources; and (iii) the decision component, which determines the desired production for the next production cycle. The three components interact as follows (Fig. 1):

At the beginning of a production cycle, the ecological component is used to determine the seeding biomass corresponding to the desired production for that cycle and to allocate the required cultivation space. The ecosystem water quality and environmental conditions are used to calculate the scope for growth of the cultivated species. In parallel, the aquatic resource production affects the biogeochemistry of the ecosystem, either through waste generation and/or uptake of particulate and dissolved substances, depending on species and culture practice. The adult individuals are subsequently harvested and transferred to the economic component at the end of the production cycle, and the harvested biomass is used by this module to calculate the revenue generated. Concurrently, in the economic component the production inputs, such as labor and capital required to produce the desirable yield (as calculated in the decision component), are determined and used to calculate the production cost. In addition, the economic component determines the marginal cost and marginal revenue in order to inform the decision component about profitability. The decision component then determines the changes in the desired production for the next cycle based on the following criteria: (i) profit maximization, based on the comparison of marginal cost and marginal revenue; (ii) the gap between demand and supply, based on the comparison of the local demand against shellfish production, in order to monitor if the market can absorb an increase in production or if there is already a surplus; and (iii) physical limit, in order to ensure that the cultivation area does not exceed the maximum available area for aquaculture, as defined by ecosystem managers.

2.1.1. Ecological and economic limits

The ecosystem carrying capacity and economic production capacity can be limited by the following factors:

1. Space limitation, which is defined by stakeholders with respect to allocation of ecosystem area to cultivation and other uses.
2. Food limitation (in the case of extensive aquaculture), which is a function of available ecosystem resources, cultivation densities and practices. It affects the growth rate of aquatic resources.
3. Aquaculture waste limitation, which causes an effect on environmental conditions such as dissolved oxygen, thereby causing a feedback on the growth rate of aquatic resources. These effects depend on the cultivation practice and on the assimilation capacity of the ecosystem.
4. Cost limitations related to the amount of inputs that can be used.
5. Diminishing returns to scale, such that each additional unit of variable input yields less and less additional output (production).
6. Profit maximization, whereby the profit maximizing firms will increase production as long as their profits will continue to rise. Profits will start to decrease beyond the output level where marginal cost equals marginal revenue.

2.2. Case study: site and data description

The MARKET model was applied to simulate shellfish production in Xiangshan Gang, a coastal embayment located in Zhejiang Province, in the East China Sea (Fig. 2) in the vicinity of the largely industrialized centre of Ningbo City.

Zhejiang Province is known for its valuable marine resources, although it is less dependent on the primary sector than China in general (Table 1). Considering the total value of all marine and inland

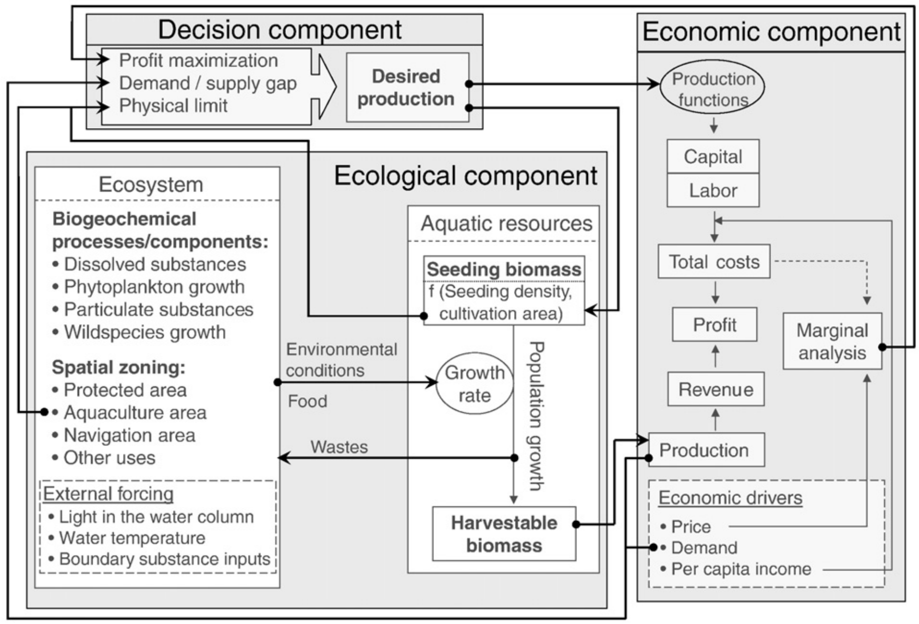
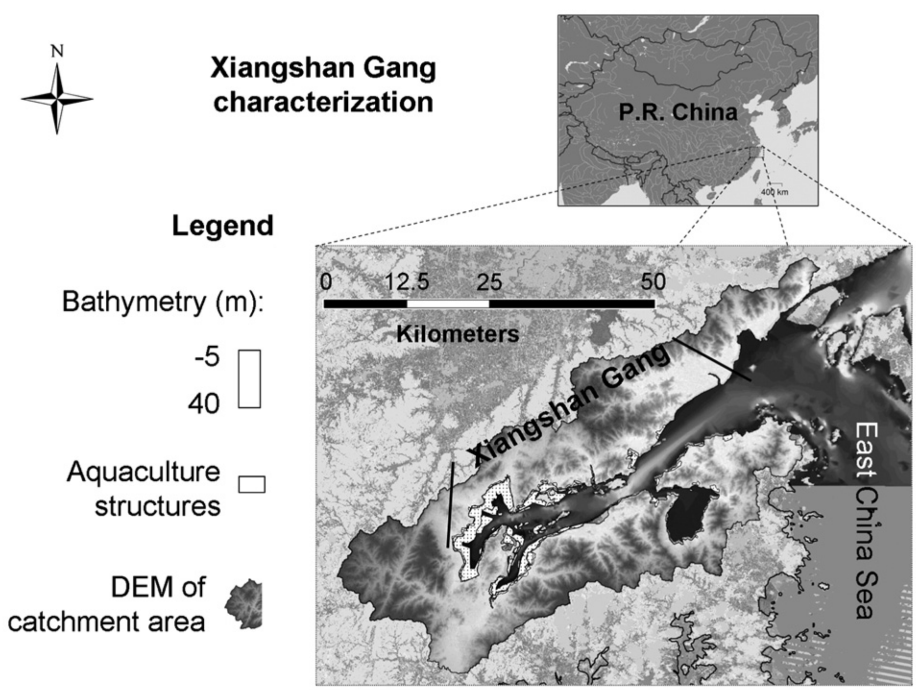


Fig. 1. MARKET conceptual model: ecological–economic interactions in mariculture.

fish farming and the direct employment it generates (Table 1) this industry creates almost 20 direct fish farming jobs per 1 million Yuan (124,000 USD) of value in fish farming. In Zhejiang, total aquatic outputs declined by 2% from 2004 to 2005, while secondary and tertiary sectors continued to grow rapidly (Information Center of General Office of Zhejiang Provincial Government, 2006). A synthesis of the case study socio-economic indicators is provided in Table 1.

The Xiangshan Gang covers an area of 365 km^2 and an annual shellfish production of about 38,000 ton (Sequeira et al., 2008). Fig. 2 provides further details about the characteristics of the bay. An ecosystem model developed for the Xiangshan Gang was used in order to simulate the shellfish production and the biogeochemistry of the system (Ferreira et al., 2008b; Sequeira et al., 2008). Data on the ecosystem and shellfish cultivation were obtained from Ferreira et al. (2008b) and Sequeira et al. (2008).

Economic data used in this study are from various sources and include: (i) data on the reference production, cost and net profit obtained in a local survey on the economics of aquaculture (de Wit et al.,



Volume (10^6 m^3)	Surface area (km^2)	Maximum depth (m)	Mean temperature (°C)	Mean salinity	Catchment area (km^2)
3,803	365	45	24	24	1,478

Fig. 2. Xiangshan Gang map and physical data.

Table 1
Case study socio-economic indicators.

	China	Zhejiang Province	Ningbo City
Population, million inhabitants	1300	47	6
Urban per capita annual disposable income, Yuan (USD)	10,397 (1290)	10,156 (1260)	26,598 (3300)
Primary sector share of economy, %	15	7	7
Fish production, million ton	47	4.9	0.9
Total fisheries value, Yuan billion (USD billion)	332 (41.2)	14.0 (1.7)	n/a
Related industry value, Yuan billion (USD billion)	126 (15.6)	3.0 (0.4)	n/a
Related services value, Yuan thousand (USD thousand)	119,400 (14,814)	300 (37)	n/a
Marine farming value, Yuan billion (USD billion)	73 (9.1)	n/a	n/a
Inland farming value, Yuan billion (USD billion)	143 (17.7)	n/a	n/a
Total fisheries employment, million jobs	7.0	n/a	n/a
Fish farming employment, million jobs	4.3	n/a	n/a

Note: Conversion to USD is shown between 'brackets' after values in Yuan considering the exchange rate at the time of study: 1 USD = 8.06 Yuan.
Compiled from FAO (2004) and NBSC (2007).

2008); (ii) the sensitivity (elasticity) of demand to price and income obtained from demand functions analysis, while the capital and labor elasticities are obtained from a production function analysis (Musango et al., 2007); (iii) other data such as production and price growth rates are from various issues of the China Statistical Yearbooks (NBSC, 2007) while the interest rate was taken from International Monetary Fund (IMF) statistics.

2.3. Model implementation

The MARKET model was implemented for shellfish production in Xiangshan Gang using a visual modeling platform (PowerSim™). Tables 2 and 3 specify the model parameters and the initial conditions of the state variables.

A key feature for implementation of the integrated ecological–economic model was to accommodate the different resolutions at which the ecological and the economic systems are studied, which are hours to days, and annual quarters to years, respectively. The scaling issue was addressed by using two different timesteps for each model, 0.01 year (3.65 days) for the ecological model and 1 year for the economic model (Table 2). The ecological model runs every timestep while the economic and decision models run only with a periodicity corresponding to its timestep, i.e. every 100 timesteps of the simulation. The simulation period considered is 50 years and the shellfish production cycle (*tp* in yr) is one year (Table 2). The seeding occurs during the first 91 days of the year (Table 2) and the harvest accumulates until the last timestep of each year (0.99 yr), at which the harvestable biomass is communicated to the economic model. The decision and economic models operate at the last timestep of each year (0.99 yr).

The implementation of each simulation block of the MARKET model (Fig. 1) is explained below.

2.3.1. Ecological component

The implementation of the ecological component of the MARKET model followed a three stage approach:

Stage 1 Decoupled ecosystem modeling. This stage comprehends simulation of Xiangshan Gang biogeochemistry and shellfish growth using an ecosystem model, which was decoupled from the MARKET model.

Stage 2 Simplification of main interactions between ecosystem model and shellfish production. In this stage the ecosystem model was used to determine the shellfish growth rate as function of cultivated area and thus of seeding biomass (given that seeding density is a constant).

Stage 3 Integration in the MARKET model of the main interactions with the ecosystem model. In this stage a population model was used to simulate the harvestable available biomass (to be used as an input in the economic model at the end of the production cycle) based on the seeding input (obtained from the decision model output at the beginning of each production cycle) and on the shellfish growth rate (obtained from stage 2).

Table 2
MARKET model parameters.

Parameter	Symbol	Value	Unit	Comment
Simulation setup				
Simulation timestep	ts	0.01	yr	
Ecological timestep	ts_{ecol}	0.01	yr	
Economic timestep	ts_{econ}	1	yr	
Simulation period	$SimP$	50	yr	
Ecological system				
Cultivation cycle	tp	1	yr	
Seeding period	sp	0.25	yr	0.00 to 0.25 yr every yr
Seeding density	n_{seed}	45	ind m^{-2}	Sequeira et al. (2008)
Weight class	S			
Weight class 1	S_1	5	g ind^{-1}	0 to 10 g ind^{-1}
Weight class 2	S_2	15	g ind^{-1}	10 to 20 g ind^{-1}
Weight class 3	S_3	20	g ind^{-1}	20 to 30 g ind^{-1}
Mortality rate	μ	0.46	yr^{-1}	Sequeira et al. (2008)
Maximum cultivation area	$MaxA$	302,950,000	m^2	83% of bay area
Ecosystem model seed weight	W	1.5	g ind^{-1}	Sequeira et al. (2008)
Economic system				
Price elasticity of demand	e_d	−0.07	(−)	Ferreira et al. (2008b)
Income elasticity of demand	e_y	0.87	(−)	Ferreira et al. (2008b)
Per capita income growth rate	r_y	0.1	yr^{-1}	NBSC (2007)
Price growth rate	r_p	0.02	yr^{-1}	NBSC (2007)
Demand growth rate	r_d	0.0856	yr^{-1}	$r_d = e_y * r_y + e_d * r_p$
Elasticity of labor	α_L	0.44	(−)	Musango et al. (2007)
Elasticity of capital	α_K	0.53	(−)	Musango et al. (2007)
Depreciation fraction	d_f	0.1	(−)	$d_f = ts_{econ}/d_p$
Depreciation period	d_p	10	yr	Assumption
Interest rate	r	0.06	yr^{-1}	IMF
Maintenance fraction	m_f	0.16	yr^{-1}	Assumption

2.3.1.1. Stage 1 — decoupled ecosystem model. An ecosystem model, developed with the widely used EcoWin2000 modeling platform (Ferreira, 1995; Nobre et al., 2005; Nunes et al., 2003; Sequeira et al., 2008), was applied to simulate the key biogeochemical features of

Table 3
Initial value of MARKET model variables.

State variable	Symbol	Initial value	Unit	Comment
Cultivation area	A	23,083,092	m^2	Sequeira et al. (2008)
Local demand	LD	37,222,000	kg	Assumed equal to initial Q
Price	P	12.5	Yuan kg^{-1}	de Wit et al. (2008)
Shellfish production	Q	37,222,000	kg	de Wit et al. (2008)
Labor	L	128,211	Man-Day (MD)	de Wit et al. (2008)
Capital	K	37,030,726	Yuan	de Wit et al. (2008)
Unit labor cost	UVC_L	7.38	Yuan MD^{-1}	de Wit et al. (2008)
Unit cost of other variable inputs	UVC_O	0.19	Yuan kg^{-1}	de Wit et al. (2008)

Xiangshan Gang as well as shellfish aquaculture (Ferreira et al., 2008b; Sequeira et al., 2008). The spatial domain of the model was divided into 24 compartments (12 horizontal × 2 vertical layers). The catchment loads (dissolved nutrients and particulate matter) and fish cage wastes were simulated as a forcing function (Ferreira et al., 2008b). The transport of substances was simulated using an offline data series of water fluxes between boxes and across the sea boundaries, provided by a detailed hydrodynamic model (Ferreira et al., 2008b). In each box the main state variables simulated were dissolved inorganic nutrients (nitrogen and phosphorus), suspended particulate matter, phytoplankton biomass, shellfish individual scope for growth and population dynamics, following the approach described for instance in Ferreira et al. (2008a).

For the simulation of feedbacks between the economic and environmental components, both the economic and the decision models should be coupled with the ecosystem model, although in the current implementation of the MARKET model simulations were made in decoupled mode.

2.3.1.2. Stage 2 — simplification of main interactions between the ecosystem model and shellfish production. In order to implement the ecological component of the MARKET model the main interactions between the ecosystem model and the aquatic resources production were simplified. It was considered that these are represented by (i) the seeding biomass (i.e. the cultivation area assuming that the seeding density is a constant) and (ii) the resulting growth of the bivalves.

The decoupled ecosystem model of the bay (Sequeira et al., 2008) was run in order to determine the shellfish growth rate as a function of the cultivated area. Several cultivation areas were used to run the ecosystem model using the same setup for the remaining initial state variables, parameters and boundary conditions. Therefore, the simulation accommodates the potential food availability constraints due to an increase in the number of filter feeders. It was found that the growth rate is inversely proportional to the cultivated area (Eq. (1)).

$$G = -2.3 \times 10^{-8} \cdot A + 20.71 \tag{1}$$

Where, G is the annual growth rate (yr^{-1}) and A is the cultivation area (m^2).

The disruption of shellfish production due to food availability, which potentially could occur as a result of an increase of cultivated area, is never reached, even when the maximum cultivated area (considered to be 83% of the bay area) is attained.

2.3.1.3. Stage 3 — integration in the MARKET model of the main interactions with the ecosystem model. In the current implementation of the MARKET model, shellfish growth provides a proxy for the ecosystem feedbacks. The ecological component was implemented by means of a population model (Ferreira et al., 2007), which was used to simulate the growth of the cultivated seed up to a harvestable size (Eq. (2)).

$$\mathrm{d}N(s,t)/\mathrm{d}t = -\mathrm{d}[N(s,t)*g(t)]/\mathrm{d}s - \mu*N(s,t) \tag{2}$$

Where, s is weight class (in g ind^{-1}, defined in Table 2), t is time (in yr), N is number of individuals (in ind) of weight class s, g is scope for growth (in g ind^{-1} yr^{-1}), and μ is mortality rate (in yr^{-1}, defined in Table 2).

Every year at the end of the production cycle the new cultivation area for the next year (Eq. (3)) is calculated as a function of previous cultivated area and rate of change in production (r_{cq}, in yr^{-1}, obtained from the decision component):

$$\mathrm{d}A/\mathrm{d}t = A*r_{cq} \tag{3}$$

At the start of each seeding period (sp, in yr, defined in Table 2) the total seeding of individuals in Class 1 (N_1, Eq. (4)) is determined based on cultivation area (A from Eq. (3)) and seeding density (n_{seed}, ind m^{-2}, defined in Table 2):

$$N_1 = A*n_{seed} \tag{4}$$

Scope for growth (g, Eq. (5)) is calculated as a proxy of the population growth (G from Eq. (1)), and thus is a function of cultivated area.

$$g = G*w \tag{5}$$

Where, w (in g ind^{-1}, defined in Table 2) is the average individual seed weight used in the ecosystem model.

At the end of the year the individuals accumulated in the harvestable classes ($N_2 + N_3$, as calculated from Eq. (2)) are converted into the harvestable biomass (HB, in kg, Eq. (6)):

$$HB = (N_2*s_2 + N_3*s_3)*\beta \tag{6}$$

Where, β is the conversion from g to kg.

Current implementation of the ecological model assumes that decisions to change production are implemented through changes in the cultivation biomass. On the other hand, the changes in the cultivation biomass affect the growth of shellfish (due to food availability) and consequently the harvestable biomass. At this stage of development, the ecosystem feedbacks are implicitly included in the MARKET model through the shellfish growth. Future developments of the model will include explicit integration of the economic and decision systems into the ecosystem model in order to monitor shellfish biodeposition as well as the role of filter-feeders on phytoplankton uptake. Phytoplankton removal equates to the reduction of coastal eutrophication symptoms, providing an additional ecosystem service.

2.3.2. Economic component

In each simulation year, the decision model calculates the desired production rate, communicates it to the economic model and thus drives the change in the production inputs (Fig. 1). The economic component of the MARKET model is divided into sub-models that simulate: (i) the harvest of the available biomass determined by the ecological model, (ii) the production inputs (labor and capital), (iii) the corresponding production cost, (iv) the generated revenue and net profit of the bivalve production for a given year, and (vi) the marginal cost and marginal revenue in order to provide information required by the decision model. The implementation of the economic model also includes simulation of the exogenous functions that drive the aquatic resource production, namely: (i) price, (ii) household income, and (iii) local demand. Both the economic drivers and sub-models are further detailed below.

2.3.2.1. Economic drivers. The economic drivers are implemented following standard economic theory. A rise in income is expected to positively influence the demand for fish and aquatic products and an increase in price is expected to negatively influence the demand for aquatic species and aquatic products (Jolly and Clonts, 1993). In the model the changes in demand (r_d, in yr^{-1}) are determined by changes in the income and prices, as defined in Table 2. Both the price elasticity of demand (e_d, Table 2) and income elasticity of demand (e_y, Table 2) were obtained from a national level demand function analysis (Ferreira et al., 2008b). This model assumes that the changes of the local demand follow the changes of the national demand, as information to derive local level demand functions was not available. The local demand (LD, in kg) forcing function (Eq. (7)) is initialized considering the local consumption data as the initial local demand (Table 3).

$$dLD/dt = r_d * LD \quad (7)$$

The local farmers are assumed to be price takers, whereby the aquatic product prices are determined by the global market. The changes in the domestic price reflect the Chinese inflation rate for the period 1995–2006. The yearly average including outliers is 2. 8%, while when excluded, the average is 1. 5% (NBSC, 2007). A constant price growth rate (r_p, in yr^{-1}) of 2% per year was therefore assumed based on the averaged inflation data. The price (P, in Yuan kg^{-1}) forcing function is given by Eq. (8):

$$dP/dt = r_p * P \quad (8)$$

In addition to price and demand the economic model is also forced by the annual growth of the per capita income (r_y, in yr^{-1}). The per capita income growth rate is used to calculate the changes in the demand (r_d), as defined in Table 2, and is also used to force the changes of the unit labor cost as defined in Eq. (23). A constant per capita income growth rate of 10% per year was assumed based on the real per capita income growth data (NBSC, 2007).

2.3.2.2. Production sub-model. The shellfish production (Q, in kg) for a given year (Eq. (9)), is based on the desired production determined for that year and is limited by the harvestable biomass simulated in the ecological system (HB, in kg, Eq. (6)). Thus, herein we assume that the harvest shellfish yield equals to the shellfish production.

$$Q = \mathrm{Min}(DQ, HB) \quad (9)$$

Where, DQ (in kg), is the desired production determined for that year, which was calculated in the previous year as the desired production for the next cycle, following Eq. (32), in the decision system.

2.3.2.3. Production inputs sub-model. This sub-model examines the capital and labor input levels resulting from the changes in the desired production:

$$dL/dt = R_L \quad (10)$$

$$dK/dt = R_K \quad (11)$$

Where, L (in Man-Day) is the labor used for the production and is calculated based on the required changes in labor inputs (R_L, in Man-Days yr^{-1}); K (in Yuan) represents the assets used in production and is calculated based on the required changes in the value of capital (R_K, in Yuan yr^{-1}).

The changes in both labor (R_L, Eq. (12)) and capital (R_K, Eq. (13)) are determined as a function of the desired change in production (R_{CQ}, in kg yr^{-1}, calculated in the decision model, Eq. (31)) and respectively on the marginal productivity of labor (MP_L, in kg Man-Days^{-1}) and on the marginal productivity of capital (MP_K, in kg Yuan^{-1}):

$$R_L = R_{CQ}/MP_L \quad (12)$$

$$R_K = R_{CQ}/MP_K \quad (13)$$

Where, MP_L and MP_K are determined following Eq. (14) and Eq. (15), respectively, as defined in Yunhua et al. (1998).

$$MP_L = \alpha_L * Q/L \quad (14)$$

$$MP_K = \alpha_K * Q/K \quad (15)$$

Where, α_L and α_K (dimensionless, Table 2) are the elasticity of labor and capital, respectively, and were determined based on the production function (Musango et al., 2007) defined in Eq. (16):

$$\ln Q = 0.44 * \ln L + 0.53 * \ln K + 1.16 \quad (16)$$

2.3.2.4. Production cost sub-model. The production cost sub-model determines the total cost of shellfish production (TC_Q, in Yuan, Eq. (17)) as the sum of the fixed cost (FC, in Yuan) and the variable cost (VC, in Yuan):

$$TC_Q = FC + VC \quad (17)$$

Where, FC and VC are calculated following Eq. (18) and Eq. (21), respectively.

$$FC = DK + IKL \quad (18)$$

Where, FC is given by the depreciation of capital (DK, in Yuan) and by the interest on capital loan (IKL, in Yuan). DK and IKL are given by Eq. (19) and Eq. (20), respectively.

$$DK = d_f * K \quad (19)$$

Where, d_f (dimensionless) represents the depreciation fraction (Table 2).

$$IKL = r * K \quad (20)$$

Where, r (yr^{-1}) is the interest rate (Table 2).

The variable cost includes the labor cost (VC_L), the maintenance cost (VC_M) and other variable costs (VC_O), all are expressed in Yuan:

$$VC = VC_L + VC_M + VC_O \quad (21)$$

The labor cost is calculated based on the labor and on the unit labor cost (UVC_L, in Yuan Man-Day^{-1}):

$$VC_L = L * UVC_L \quad (22)$$

The unit labor cost changes as a function of the per capita income growth rate (r_y, in yr^{-1}, defined in Table 2):

$$dUVC_L/dt = r_y * UVC_L \quad (23)$$

The maintenance cost is determined as a fraction (m_f, defined in Table 2) of the capital (K) as defined in a local economic survey (de Wit et al., 2008) and following Eq. (24):

$$VC_M = m_f * K \quad (24)$$

The other variable costs include costs of feeding, seeding and interest on loan among others. This variable is calculated based on the shellfish production (Q, in kg, Eq. (9)) and on the unit cost of other variables (UVC_O, in Yuan kg^{-1}):

$$VC_O = Q * UVC_O \quad (25)$$

The unit cost of other variables changes as a function of the price growth rate (r_p, in yr^{-1}, defined in Table 2):

$$dUVC_O/dt = r_p * UVC_O \quad (26)$$

2.3.2.5. Net profit sub-model. The dynamics of net profit (*NP*, in Yuan, Eq. (27)) are determined by the revenue (derived from the dynamics of production output and price) and the total cost incurred (which includes fixed and variable costs):

$$NP = (Q*P) - (FC + VC) \tag{27}$$

2.3.2.6. Marginal cost and marginal revenue sub-model. For each economic timestep the marginal cost (*MC*, in Yuan kg^{-1}) is determined as the increase in total cost that results of producing an additional unit of shellfish:

$$MC = \Delta TC / \Delta Q \tag{28}$$

For calculation of *MC* we consider an output increment of one kg of shellfish ($\Delta Q = 1$ kg). Thus, for every 1 unit of additional *Q*, Eq. (28) reduces to:

$$MC = TC_{Q+1} - TC_Q \tag{29}$$

Where, TC_{Q+1} (in Yuan) is the total cost to produce $Q+1$, and TC_Q (Eq. (17)) the total cost as calculated previously for *Q*. TC_{Q+1} is calculated using the production cost sub-model (Eq. (17) to Eq. (26)) to compute the cost of the inputs (labor and capital) needed to produce $Q+1$. On the other hand, the required labor and capital to produce the additional output are determined by multiplying 1 kg of shellfish by the inverse of marginal productivity of labor ($^1/_{MP_L}$ which expresses as Man-Days kg^{-1}) and the inverse of marginal productivity of capital ($^1/_{MP_K}$ which expresses as Yuan kg^{-1}), respectively.

Assuming that the shellfish farmers are price takers, the marginal revenue (*MR*, in Yuan kg^{-1}) was equated to the price of shellfish (*P*, in Yuan kg^{-1}, Eq. (8)).

$$MR = P \tag{30}$$

Both marginal cost (*MC*) and marginal revenue (*MR*) are used by the decision model for calculation of the profit maximization criteria.

2.3.3. Decision component

The decision component is the engine of the MARKET model. This simulation block determines the production in the following year, therefore driving both the ecological and economic components. In the MARKET model it is assumed that the farmers' decision is based on (i) the profit maximization, (ii) the gap between demand and supply, and (iii) the available area for aquaculture activities, i.e. the physical limits. Each of the three criteria is further detailed below:

i) Profit maximization: the local farmers are assumed to be perfectly rational and that their interest in aquaculture production is to maximize individual profit. Therefore, they will aim to increase production only up to an output level whereby marginal cost equals marginal revenue. In this analysis, the farm managers are assumed to have knowledge on the cost and demand functions facing the shellfish production and about other actors in the system. Although none of these conditions are likely to be met in reality, these provide a baseline economic decision-making rule to maximize profit in order to test the application of the MARKET model. Both marginal cost and marginal revenue values are provided by the economic model (Eq. (29) and Eq. (30)). If the marginal revenue is greater than the marginal cost ($MR>MC$) the decision model defines an increase in desired production for the next period and the inverse occurs when the marginal revenue is less than the marginal cost ($MR<MC$). If the marginal revenue equals marginal cost ($MR=MC$) then the model decides to maintain the desired production for the next period at current production level.

ii) Demand/supply gap: is calculated as the difference between the local demand and the shellfish production, both given by the economic model (Eqs. (7) and (9)). It indicates whether the demand is met by production (if $Q \geq LD$), or if the market can absorb an increase in production (if $Q<LD$).

iii) Physical limit: the farmers can expand up to a maximum available area for aquaculture ($A = MaxA$). In the model the maximum cultivation area is a parameter of the ecological component (Table 2). This area should be defined by ecosystem managers based on a zoning policy decision or simply based on the physical limits of the ecosystem.

The decision on whether to increase, decrease or maintain production is simulated based on the decision rules shown in Fig. 3. If all the three criteria are favorable to increase production ($MR>MC$ AND $LD>Q$ AND $A<MaxA$), the desired production increases at a percentage of current year production. If the current profitability is negative ($MR<MC$) then the decision model defines a decrease in the desired production which is proportional to the current year production. If none of the previous conditions are met and if the maximum profitability is achieved ($MR=MC$), or demand is met ($Q \geq LD$) or the maximum cultivation area is attained ($A \geq MaxA$) then the decision model maintains the current year production.

The change in the quantity that aquaculture managers want to produce in the next cycle, i.e. the desired change in production (R_{CQ}, in kg yr^{-1}), is calculated as a fraction of current year production by means of Eq. (31):

$$R_{CQ} = Q*r_{cq} \tag{31}$$

Where, *Q* (in kg) represents the current year production and is calculated in the economic model (Eq. (9)); r_{cq} (in yr^{-1}), is the annual change rate in production and is conditioned by the decision whether to increase, decrease or maintain production (according with Fig. 3 and as explained above). Depending on the decision taken r_{cq} is given as:

(i) If decision is to increase production, then the rate of change in production is 10% per year of current production ($r_{cq} = 0.1\ yr^{-1}$);
(ii) If decision is to decrease production, then the rate of change in production is −30% per year of current production ($r_{cq} = -0.3\ yr^{-1}$);
(iii) If decision is to maintain production, then the rate of change in production is 0% per year of current production ($r_{cq} = 0.0\ yr^{-1}$).

Further research is needed to understand how this decision is normally taken in the real world in order to improve the definition of the rate of change in production.

The desired production for the next cycle (*DQ*, in kg) is then given by current production (*Q*) and by the desired change in production for the next cycle ($R_{CQ}*tp$):

$$DQ = Q + R_{CQ}*tp \tag{32}$$

Where, *tp* (in yr) is the shellfish production cycle period (defined in Table 2).

2.4. Model assessment and scenario definition

At this stage of development and given the deterministic nature of the MARKET model, it cannot incorporate the randomness involved in decisions by individual farmers. In addition, it does not integrate the complex dynamics that govern for instance a policy change that decides a shift from shellfish to finfish or macroalgal production. In order to validate the MARKET model at that level, a very specific

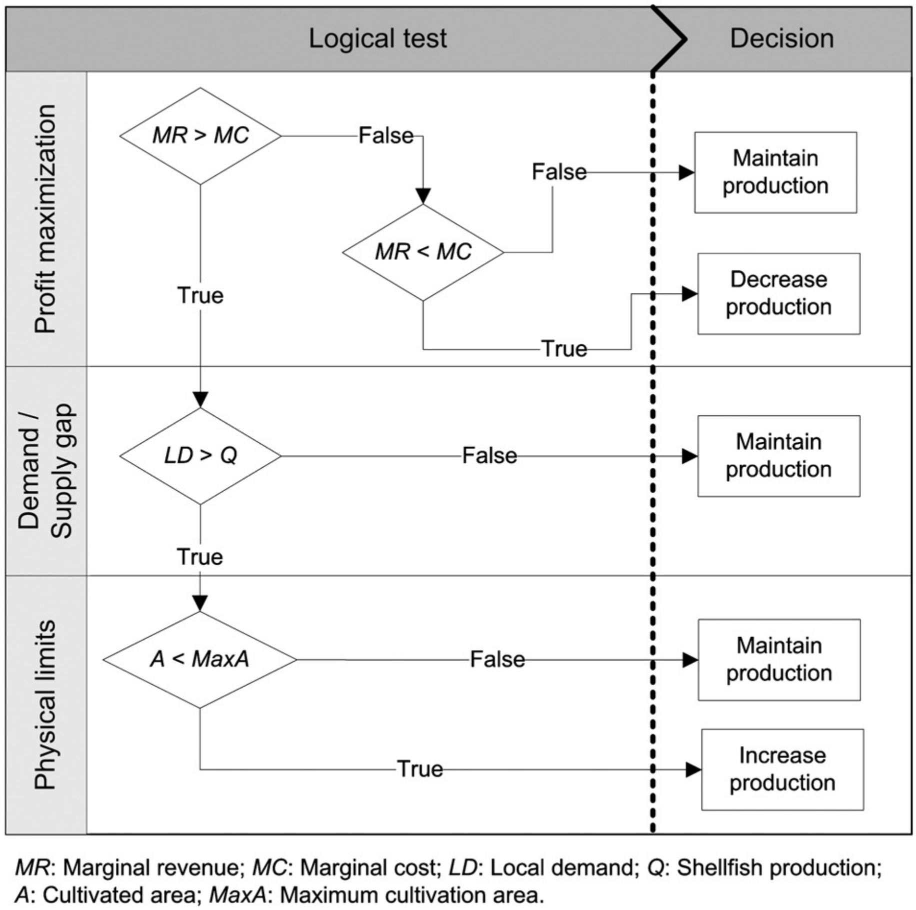


Fig. 3. Decision model implementation: logical test for decision about increase, decrease or maintaining current production.

dataset would be required: a data series of both economic production and environmental factors for a given ecosystem where the main changes in aquaculture production are only constrained by the ecological and economic factors in a perfectly rational way.

The applicability of the model was thus assessed by comparing the general trends of simulation results with the expected outcomes according to standard economic theory for consumption and production and according to ecological economics theory: It is expected that shellfish is a normal good, meaning that rising income will lead to rising demand and vice-versa. It is also expected that a rising demand will lead to an expansion in farming activities up to a level that is both economically profitable and sustained by the ecosystem. In order to support the comparison with expected results a set of scenarios was defined (Table 4) aimed to test the model response to changes in price and income growth rates, and maximum cultivation area. Another reason to run these scenarios was to demonstrate the capabilities of the MARKET model to simulate relevant management scenarios. For instance scenario 3 exemplifies a management decision to set a lower maximum cultivation area as compared to the standard scenario. Scenario 4 develops this by introducing a compensation measure to farmers whereby the reduction of the maximum cultivation area is followed by a price increase.

Table 4
Scenarios analyzed in the MARKET model.

Scenario	Price growth rate (% per year): r_p	Income growth rate (% per year): r_y	Maximum cultivation area (% of bay area): *MaxA*
Standard	2%	10%	83% of bay
Scenario 1	1%	Standard	Standard
Scenario 2	Standard	5%	Standard
Scenario 3	Standard	Standard	42% of bay
Scenario 4	3%	Standard	42% of bay

3. Results

The standard simulation results indicate that the production is limited by the maximum cultivation area in the 27th year (Fig. 4b). Afterwards, the economic limitation to production (marginal cost equals marginal revenue) is experienced after 10 years in the 37th year (Fig. 4c). These two limitations in production are visible in the net profit curve shown in Fig. 4d.

In scenario 1 the reduction of half the price growth rate ($r_P = 1\%$ per year, Table 4) is tested. The economic limit to production (marginal cost equals marginal revenue) in this scenario is reached sooner than in the standard and other simulations (Fig. 4c). The net profit also decreases (Fig. 4d). This is because the price is a major determinant in the profitability of the aquatic operations. Therefore, with other variables growing at the rate of the standard simulation, the profitability decreases.

In scenario 2, a decrease of the per capita income growth rate to half the standard simulation ($r_y = 5\%$ per year, Table 4) is tested, while the values of price growth rate and cultivation area are the same as in the standard simulation (Table 4). The income growth rate does influence the demand: with a lower income growth rate, the demand in scenario 2 is lower than in the standard scenario (Fig. 4a) and the exploitation rate is therefore lower (Fig. 4b). As a result of the reduced harvest, there is less pressure on the aquatic resources. Although the

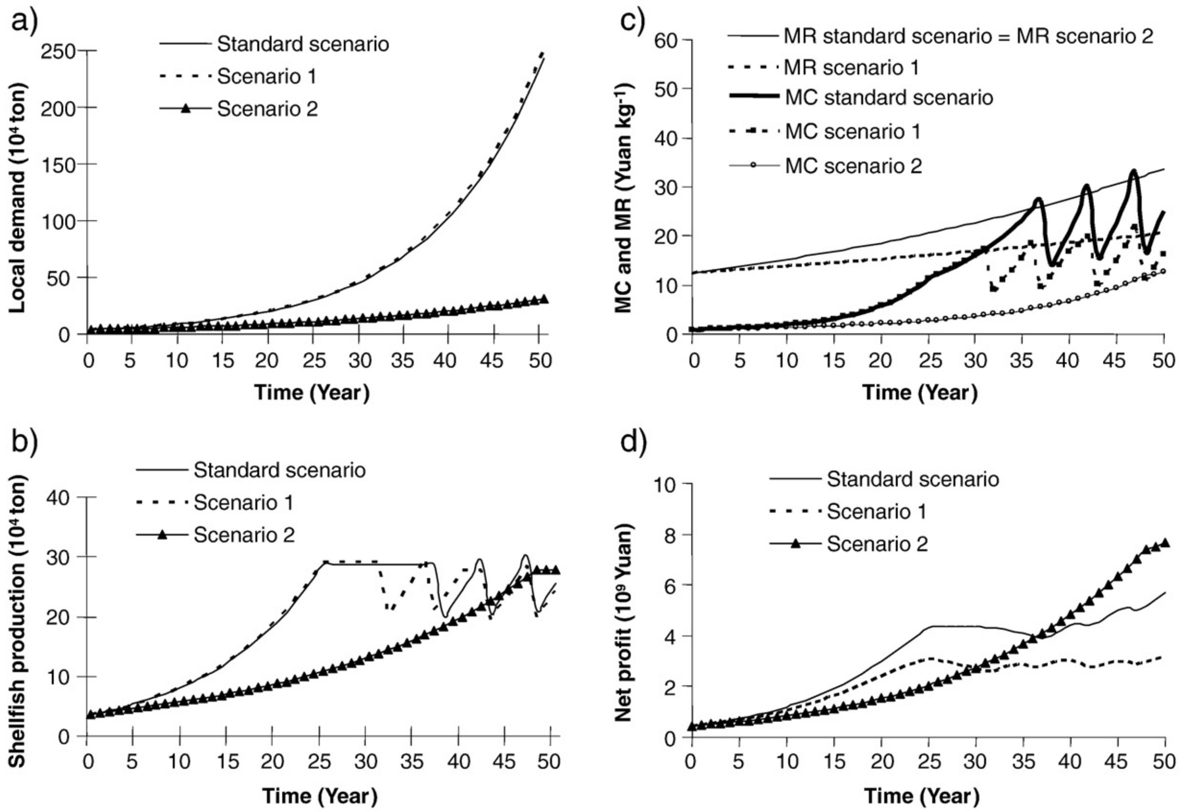


Fig. 4. Simulation results for standard scenario, scenario 1 and scenario 2 for: a) local demand (*LD*), b) shellfish production (*Q*), c) marginal cost and revenue (*MC* and *MR*), and d) net profit (*NP*).

demand is lower than in the standard simulation, in the long run the shellfish production in scenario 2 presents higher profits than in the standard simulation: the marginal cost is less than marginal revenue in the entire simulation and from 40th year, the net profit in scenario 2 diverges beyond the standard simulation (Fig. 4d). This outcome is further explored in the discussion section.

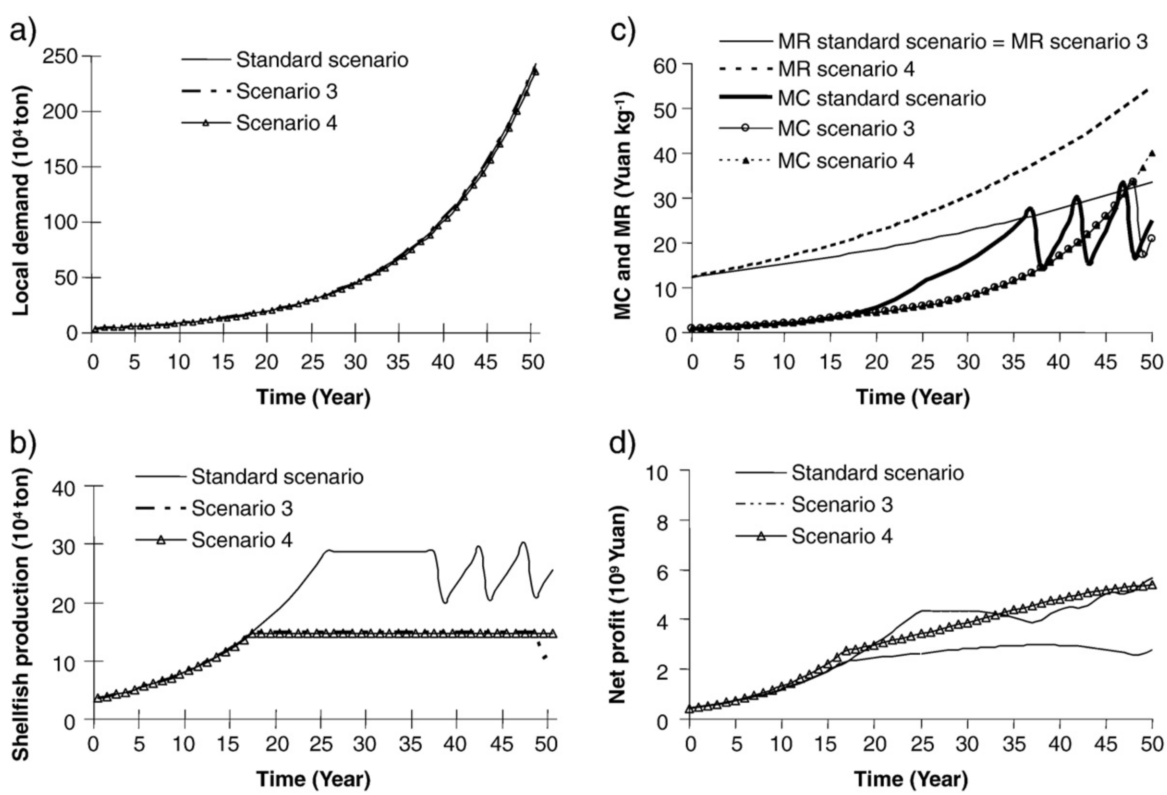


Fig. 5. Simulation results for standard scenario, scenario 3 and scenario 4 for: a) local demand (*LD*), b) shellfish production (*Q*), c) marginal cost and revenue (*MC* and *MR*), and d) net profit (*NP*).

In scenario 3, a decrease in the maximum cultivation area ($MaxA=42\%$ of total bay area, Table 4) was tested. This can simulate for instance a management decision of allocating more area of the bay for other purposes such as tourism or navigation. Up to the point where the physical limit to production is achieved, which occurs at the 18th year, all the variables (including net profit) for standard scenario and scenario 3 coincide (Fig. 5), given that the only difference between these two scenarios is the maximum cultivation area. From the 18th year, the limitation in the production area reduces the amount of harvestable biomass in scenario 3 compared with standard scenario (Fig. 5b). This further leads to reduced profits in scenario 3 compared with standard (Fig. 5d). However, it is interesting to note that due to the lower production over time (from 18th year) the marginal cost increases at a lower rate causing a decrease in profitability ($MC=MR$) only at the 47th year, whereas in the standard scenario marginal cost equals marginal revenue in the 37th year.

Scenario 4 combines the reduction of maximum cultivation area (also simulated in scenario 3) with an increase in the price growth rate ($r_P=3\%$ per year, Table 4). This scenario can exemplify a policy measure to compensate for the limitation on the aquaculture expansion potential. The outputs for this scenario show that from the 18th year the shellfish production is less than the amount simulated in the standard scenario (Fig. 5b), however, given the increase in price growth rate, the profits are sustainable in the long run: the marginal cost is less than the marginal revenue in the entire simulation (Fig. 5c) and the net profit is in the same range as the net profit for the standard simulation (Fig. 5d). The shellfish production for scenario 4 and scenario 3 are also similar except with a slight difference for scenario 3 in the 47th year. This is because at that point, the marginal cost for scenario 3 equals marginal revenue, which implies a decision to decrease production. This occurrence is mainly explained by the lower price growth rate for scenario 3 than for scenario 4.

4. Discussion

A comparison of the model results for all the simulations, as discussed below, indicates that the MARKET model followed the expected trends regarding the standard economic theory for consumption and production. Likewise the interrelationship between net profit, physical space and food limitation was modeled successfully, according to ecological economics theory.

Since the income growth rate in scenario 2 ($r_y=5\%$ per year) is half than for other scenarios ($r_y=10\%$ per year), the local demand in scenario 2 is significantly lower (Figs. 4a and 5a). On the other hand, given that the model assumes price as inelastic, the proportional change in local demand due to changes in price growth rate is lower: scenario 1, where the price growth rate is lowest ($r_p=1\%$ per year, Table 4), when compared to scenarios that consider an equal income growth rate of 10% per year (standard scenario, scenario 3 and scenario 4, Table 4) shows a slightly higher local demand (Figs. 4a and 5a).

In the scenario with a lower demand (scenario 2) the harvested shellfish was reduced (Fig. 4b). In the long run, production was limited by the maximum cultivation area in all the scenarios (Figs. 4b and 5b). This outcome indicates that the current annual rates for shellfish demand are not sustainable over extended periods of time in this ecosystem. From the ecosystem perspective this restriction was only caused by the physical limitation given that the ecosystem model results indicate that the food available suffices to yield the production up to the maximum cultivation area of 83% of the Xiangshan total area. Nevertheless, this occurs with a slower scope for growth as described in Eq. (1).

Following the physical limitation, the standard scenario, scenario 1 and scenario 3 experienced an economic limitation to production (reached when marginal cost equals marginal revenue, shown in Figs. 4c and 5c), while scenario 2 and scenario 4 did not. The explaining variables were a combination of price, production level and factors affecting the production cost: The comparison of scenario 1 ($r_p=1\%$ per year) with the standard scenario ($r_p=2\%$ per year), and of scenario 3 ($r_p=2\%$ per year) with scenario 4 ($r_p=3\%$ per year) highlighted the impact that a lower price growth rate has on economic limitation to production: in scenario 1 it is reached sooner than in the standard scenario and in scenario 3 it is reached at 47th year while in scenario 4 it is never reached (Figs. 4c and 5c, respectively). The comparison of scenario 3 with the standard scenario indicated that the lower production level in scenario 3 caused the marginal cost to equalize with the marginal revenue later than in the standard simulation (Fig. 5c). In scenario 2, where the only difference from the standard scenario is a lower income growth rate and consequent lower demand, the economic limitation to production ($MC=MR$) was not reached, while it did occur in the standard scenario (Fig. 4c). The main explanation is the lower production level (caused by the lower demand) together with the effect of the lower income in the cost of labor for the shellfish production (as unit labor cost changes as a function of the per capita income growth rate in the model).

An interesting outcome of scenario 2 was that although the lower income resulted in a lower demand, it also caused a decrease in production cost which resulted in a net profit dynamics that in the long run exceeded the net profit of the standard scenario (Fig. 4d). This scenario raises the issue that a lower demand does not always imply a corresponding decrease in net profit. This is a topic for further research in the context of economic policy mitigation plans: MARKET or other similar models can support a more in-depth analysis, e.g., to determine where to target public intervention. In this case, if any public intervention took place, it should focus on the promotion of social security (due to the lower income), while private fish farmers were protected from the lower demand. In the remaining scenarios, the net profit dynamics followed the expected results: the decrease in price caused a decrease in profits and vice-versa, as shown by comparison of scenarios that differ only in price (the standard scenario with scenario 1 in Fig. 4d, and scenario 3 with scenario 4 in Fig. 5d); the reduction of the production level due to the reduction of the cultivation area also lead to a decrease in profits (as tested in scenario 3 compared with standard scenario, Fig. 5d). For all the simulations performed within our case study, the profits of shellfish production were assured.

5. Conclusions

The MARKET model allows for an integrated dynamic analysis of (i) the demand for mariculture products, (ii) economic production and cost limiting factors, (iii) the biological growth of aquatic resources, (iv) interactions with the environmental conditions and (iv) the spatial limitations of culture in coastal ecosystems. Our approach can contribute to mariculture management and for implementation of an ecosystem approach to aquaculture (EAA).

Simulation of shellfish production in a Chinese embayment was chosen as a case study illustrating the implementation of the MARKET model. A key feature of the model implementation was to incorporate the different time scales at which the ecological and economic systems function. In this study, we have used several management scenarios to show that the model reproduces the expected trends and provides further insights. In all the scenarios, production in the long run does not meet increasing demand. In this case study the physical limitation of the bay was the first limiting factor for all the scenarios, that is, space is expected to impose limitations on production before it becomes less profitable to expand production. Overall, the MARKET model can help to understand the succession of the limiting factors in mariculture industry and whether the production can meet the demand for aquatic resources.

The MARKET model can be widely applied, provided that case-specific information exists on shellfish demand, price, income, production functions, physical area available for cultivation, and environmental conditions that have an effect on the growth of aquatic resources and are affected by its production. It is recommended that future MARKET model developments include: (i) an improvement of the decision model, in particular for decisions by farmers about changes of production level, (ii) explicit dynamic coupling with an ecosystem model, and (iii) implementation for other aquaculture species and culture practices, especially those that normally raise more concerns related with environmental management, such as finfish monoculture.

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