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Research, part of a Special Feature on A Systems Approach for Sustainable Development in Coastal Zones

Addressing Sustainability of Clam Farming in the Venice Lagoon

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ABSTRACT. The clam fishing and aquaculture system in the Venice Lagoon still appears insufficiently resilient to buffer external and internal perturbations, such as productivity fluctuations, unregulated fishing, and market related dynamics, despite the efforts of regional and local authorities to achieve the sustainable development. According to the System Approach Framework (SAF), based on previous studies and stakeholder interactions, we developed a model integrating ecological, social, and economic (ESE) aspects. We chose the aspects necessary to represent the essential dynamics of major ecological, social, and economic clam farming system components to project the consequences of implementing alternative management policies and to address the ecological and social carrying capacity. Results of the simulations suggest that a properly managed farming system can sustain an acceptable income and support the local community, while reducing negative environmental impacts, social conflicts, and consumer health risks and improving system resilience. The results highlight the importance of an interdisciplinary, participatory, and adaptive approach in planning the management of this important renewable resource.

Key Words: *clam farming; model integration; social carrying capacity; System Approach Framework; Tapes philippinarum; Venice Lagoon*

INTRODUCTION

Multiple-use conflict is a common issue in European coastal zones. Without proper management, the unregulated superposition of drivers may lead to a chronic conflict among hardened stakeholders or to the selective survival of the few more relevant activities, with a drastic reduction of the system complexity and the consequent loss of its adaptive capability. In particular, socioeconomic activities that have a local/marginal impact on the global economy are at risk of being badly managed because they might require efforts that are apparently too large in comparison to the benefits they provide. In these cases, unplanned dynamics can emerge and drive a system toward unwanted configurations. Exploitation of the clam (*Ruditapes philippinarum*) resource in the Venice Lagoon is a case in point (Solidoro et al. 2010). In fact, when it started, this activity was considered little more than another fishing activity and gathered little attention. Once it became clear that its ecological-social-economical (ESE) dimensions were not negligible, the system had already developed along an undesirable path, difficult to correct. In a few years the system overshot its ecological and social carrying capacities, generating environmental and social concerns. Catches increased during the 1990s, reaching a peak at the end of the decade, and subsequently declined (Fig. 1). Employment greatly fluctuated too, whereas environmental impact has remained high. Different stakeholders have shown different attitudes toward clam farming in the Venice Lagoon, sometimes conflicting with each other.

Actually, the clam business can be roughly estimated at about €85-100 million/year. According to MAV-CVN 2008, around 1300 people work as clam harvesters, mainly residents of the lagoon islands and the town of Chioggia. The clam licensed fishing fleet is formed of 400 small fishing boats and 80 fishing vessels that employ vibrating dredgers (Zentilin et al. 2008, Torricelli et al. 2009).

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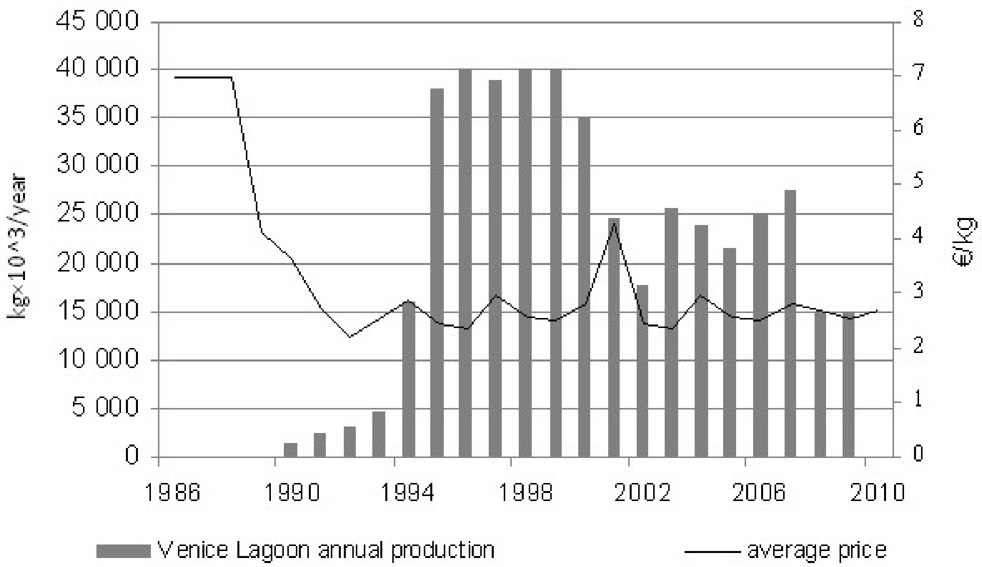
Fig. 1. Time course of clam production (first axis) and market price (second axis) in the Venice Lagoon (Zentilin et al. 2008; Dr. Chiaia, GRAL, *personal communication*).



It has also been estimated that around 200 people are fishing illegally, with about 500 tons, 2% of total production, confiscated each year (www.gral.venezia.it).

Open-access clam fishing started in the Venice Lagoon at the end of the 1980s; it expanded traditional fisheries to include clam fishing, which was more profitable, and stimulated a large increase in fishermen including those without previous specific experience. Clam fishing soon grew out of control and also expanded into prohibited and polluted areas, therefore production quality and safety standards could not be ensured. The dredging tools themselves have negative impacts on the environment, i.e., biodiversity, sea grass beds, and sediment loss (Badino et al. 2004, Pranovi et al. 2004, Boscolo et al. 2009), requiring spatial limitation of harvesting activity to mediate between clam farmer requirements and other Lagoon uses. Social tensions and conflicts arose among the fishermen and between the fishermen and local authorities.

Since the 1990s local institutions made several attempts to promote a transition from an open-access system to extensive aquaculture (Torricelli et al. 2009), to limit impacts and to preserve other natural services of the lagoon. Local institutions also made efforts to manage clam recruits (seed size of 10-14 mm) that are taken from natural nursery areas in the lagoon and, to a lesser extent, that are imported from other sites. However, a rational integrated management of this resource has not been achieved. Social issues persist including natural clam seed provisions and conflicts continue among fishermen to obtain more productive areas. Illegal fishing still occurs. The presence of rule-breakers has worsened the problem by encouraging other individuals to behave illegally and renewing open-access fishing to all areas, including prohibited ones. The persistence of this conflict is locally well known; at least once a month local newspapers report news related to illegal clam fishing. Videos on clam seizing can be seen on YouTube (April 2011; www.youtube.com/watch?v=kbuwWGW4zCM). Fishing outside the designated area continues because of economic pressure to achieve a higher profitability. Local authorities believe instead that the economic problem is mainly due to improper management of the concessions.

Many technical and research studies addressing different aspects of the clam issue in the Venice Lagoon have provided support to local authorities in their management of clam producing areas. Research addresses clam biology (Pellizzato and Da Ros 2005, Pellizzato et al. 2005), habitat suitability

(Pastres et al. 2001, GRAL 2006, 2009, MAV-CVN 2008, Torricelli et al. 2009), clam growth (Solidoro et al. 2000), production carrying capacity (Pastres et al. 2001, Melaku Canu et al. 2010), economics (Boatto et al. 2005, Nunes et al. 2004) and governance (Nunes et al. 2008), but the integration of the ecological and socioeconomic dimensions has only been approached in a simplified way (Pastres 2001, Solidoro et al. 2003, Melaku Canu et al. 2010).

We believe that a fuller integration of ESE components, made with the involvement of local stakeholders and their estimation of sustainable productivity and employment, is needed for proper clam resource planning and will eventually improve system resilience. In this context, integrated modeling tools can be helpful because they can be used for vision sharing, demonstrative scenario analysis, understanding the system complexity, and thus in making choices through increased awareness. This goal will likely support the development of local governance, which is recognized to be the key for local resilience (Kajer 2004, Kaufmann et al. 2009).

In this paper, we address the ESE sustainability of the exploitation of the clam in the Venice Lagoon. In particular we explore ecological and social carrying capacity of clam farming (sensu McKindsey et al. 2006) in the lagoon. This implies the need to consider not only the level of clam production, as opposed to lagoon productivity, but also the associated externalities. Clam management needs to respect the trade-offs between the need to protect lagoon ecosystem quality and related services and the socioeconomic demands.

The methodology follows the System Approach Framework (SAF; T. S. Hopkins, D. Bailly, and J. G. Støttrup, *unpublished manuscript*). Alternative management scenarios were identified, with stakeholder involvement, considering spatial and technical constraints, the annual seed availability, and evaluating alternative options for seed provision in terms of provenience (natural or from hatchery), cost, and quantity. To explore the dynamics occurring in the Venice Lagoon clam system under those scenarios, we integrated an ESE model using a biogeochemical, a clam bioenergetic and population dynamic, and an economic model. We therefore explore the productivity of alternative exploitation strategies in terms of production, externalities, income, and number of farmers sustained, i.e., maximum employment. We also address uncertainty in model output giving final results by using a precautionary approach.

METHODS

Policy-stakeholders involvement

To promote vision sharing and participation, we contacted local stakeholder groups (Table 1) with an interest in clam farming issues in the Venice Lagoon, gathering different feedbacks and comparing ideas and expectations. Surprisingly, fishermen and management institutions were less motivated to participate. We interpreted this reluctance to be the result of frustration, political conflicts, and perceived risks in taking an open position. Moreover, fishermen were not motivated to participate because they did not recognize political/institutional leadership in our work and they did not see an immediate payback. Only one consortium representative participated, sharing knowledge and exploring scenarios. We had four meetings with the director of GRAL, a mid-level institution with management tasks regarding *Tapes philippinarum*. The Venice Municipality (Environment Sector) was interested in meeting and sharing results. Local interest groups, Osservatorio Laguna and Vela al Terzo, a recreational traditional nautical association that expressed concerns about the environmental impact of illegal fishing, also participated. Consumer Association members (Confconsumatori) confirmed those worries (Appendix 1).

The SWOT analysis

A summary of key elements in terms of strengths, weaknesses, opportunities, and threats (SWOT) characterizing the Venice clam system has been derived from stakeholder interactions and literature review and is presented in Table 2. It has been used to focus the choice of processes to be included in the model and of model output, as well as to guide result interpretation. In this framework we explored the opportunity of addressing an overall sustainable clam system management following an integrated approach.

Table 1. Stakeholders involved in the research.

Stakeholder type	Stakeholder name	Functions
Economic	Fishermen, market, etc.	Harvest, culture, cleaning, etc.
Institutions with management tasks	Province of Venice	Fisheries/aquaculture plan in Venice Lagoon
	Regione Veneto	Sanitary legislation application
	Comune di Venezia	Lagoon protection
	Osservatorio Laguna	Natura 2000, Habitat Directive implementation
	MAV-CVN	Lagoon area allocation Lagoon protection,
Mid-level management institution	GRAL, Veneto Agricoltura	Implementation of *Tapes philippinarum* management plans.
Institutions without management tasks		
Other associations	Consumer association: Confconsumatori Recreational association: Vela al terzo	Citizens associations

The DPSIR analysis

According to the drivers, pressures, states, impacts, and pressures (DPSIR) analysis (Fig. 2), clam growth depends on the local trophic status whereas the quality of clam production is influenced by toxic contamination of water and sediment. The findings highlight the importance of a proper description of nutrient and pollutant cycles and trophodynamics, which are in turn influenced by transport processes. The scheme also emphasizes that clam dredging causes sediment resuspension and increased water turbidity, removal of organic biomass, toxic mobilization, and an impact on sediment that significantly impedes other activities in the fished area. In aquaculture, impacts are reduced because the surface is limited and harvesting is done only at the end of the growth season.

The integrated ESE model

Using results of stakeholder discussions, SWOT and DPSIR analysis, and previous knowledge, we constructed a simulation model by integrating major biogeochemical and ecological components with the most relevant economic processes of clam farming (Fig. 3), using the ExtendSim 7 platform. A 3D biogeochemical model driven by nutrient loads and meteorological conditions simulates space-time distributions of biogeochemical variables, which constrain, as a boundary condition, the simulated dynamics of biogeochemical properties within an aquaculture concession. A bioenergetic model for clam growth and a population dynamic model for clam density describe the time course of clam biomass within aquaculture concession as a function of biogeochemical properties, water temperature, and aquaculture management strategy. A bioaccumulation module defines toxic concentrations within market size mollusks and

Table 2. Strengths, weaknesses, opportunities, and threats (SWOT) analysis of clam farming in the Venice Lagoon. Adapted from Torricelli et al. 2009.

SWOT ANALYSIS CLAM FARMING IN VENICE LAGOON	
STRENGHTS	WEAKNESSESS
High lagoon suitability to clam growth High productivity Nursery areas producing natural seeds Good scientific knowledge of the environmental system and of the clam's biology	Low education Low traditional knowledge Low trust of local consumers Illegal market Illegal fishing in polluted areas Low efficiency of governance network Sediment composition alteration
THREATS	OPPORTUNITIES
Over fishing Loss of nurseries and suitable clam farming area for other uses Climate change	Promoting education Promoting comanagement Developing technology (hatcheries) Diversification Product traceability and certification Integrated management following a systemic approach Common Fisheries Policy: FLAG based on territorial approach

helps to define their selling price. Starting from simulated productivity, the economic module computes prices, costs, externalities, and other economic parameters that concur with the evaluation of profitability and sustainability of the exploitation strategy analyzed. To reduce computation time to a level that permits interactive sessions, the 3D biogeochemical model is coupled off-line and run in advance. This model implies acceptance of the concept that seston depletion within aquaculture concessions has no impact on seston concentration in the remaining, much larger, lagoon area, an approximation that was found to be valid by Melaku Canu et al. (2010).

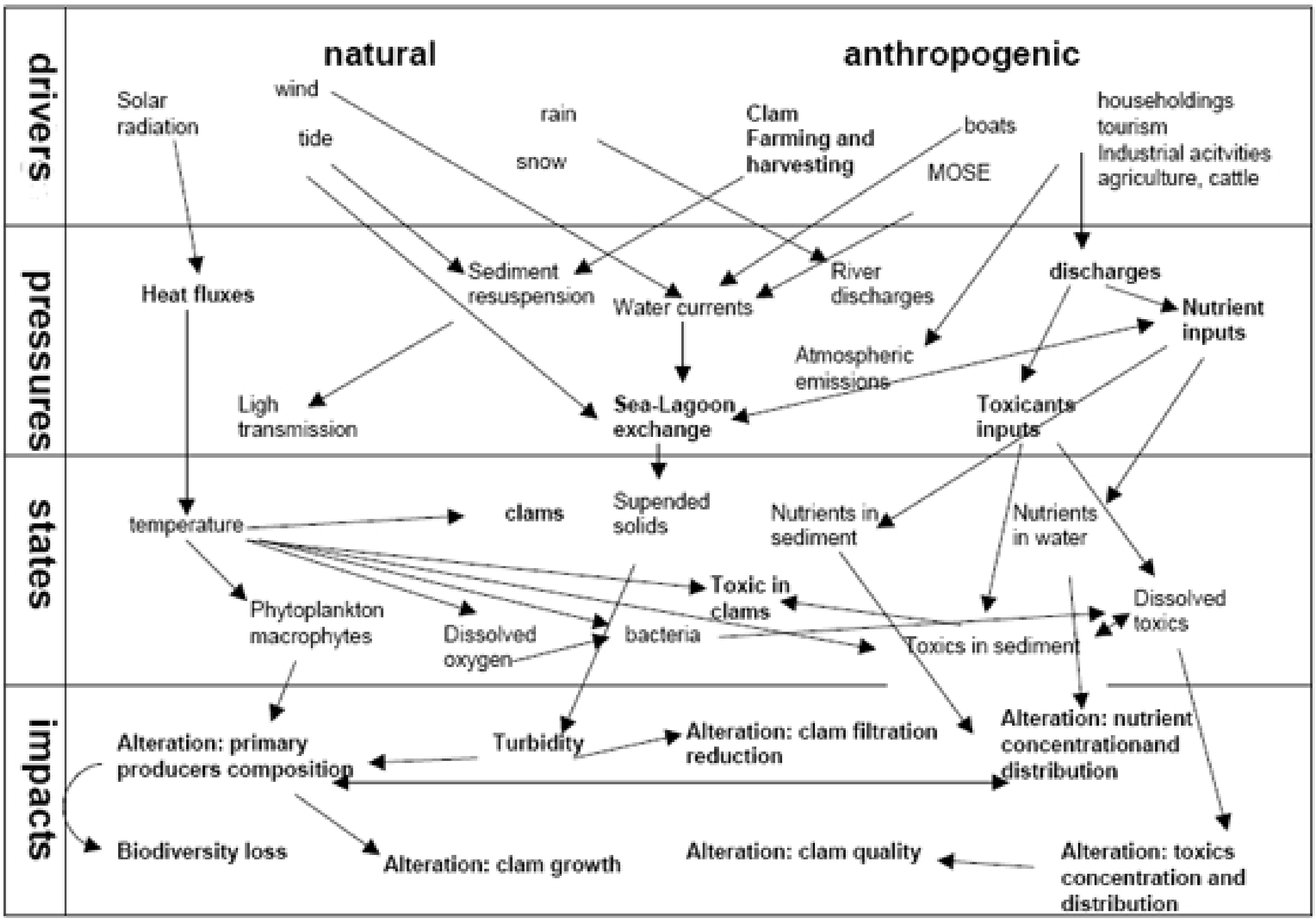
The biogeochemistry model

We used 3-D tropho-dynamic model results as biogeochemistry inputs to better resolve the spatial variability. The 3D Trophodynamic Diffusive Model (TDM; Solidoro et al. 2005) is a coupled physical-biogeochemical model specifically developed for the Venice Lagoon. Transport processes are described by a simplified version of the advection-diffusion equation, which is suitable for simulating processes that occur at time scales longer than tidal cycles (Dejak et al. 1998) and reduces the computational cost to acceptable values, even for multidecadal runs (Cossarini et al. 2008). The set of biogeochemical state variables includes phytoplankton, zooplankton, nitrate, ammonia, phosphate, nutrient content in detritus and upper sediments, and dissolved oxygen. The microbial loop is implicitly included in the parameterization of recycling processes.

The bioaccumulation model

The bioaccumulation model allows the estimation of the lipophilic contaminants concentration, such as PCBs and dioxins, in clam tissues on the basis of site specific data concerning the contamination of water and sediment, the physico-chemical properties of the toxicants and the physiology and ecology of the target organisms. Model equations are based on the more general food-web bioaccumulation models thoroughly described elsewhere (Arnot and Gobas 2004, Micheletti et al. 2007, Ciavatta et al. 2009) and are described in the Appendix 2. The model uses a steady state assumption, likely to be satisfied in shallow water environments. It was tested against clam

Fig. 2. Drivers, pressures, states, impacts, and pressures (DPSIR) scheme of processes related to clam harvesting in the Venice Lagoon.

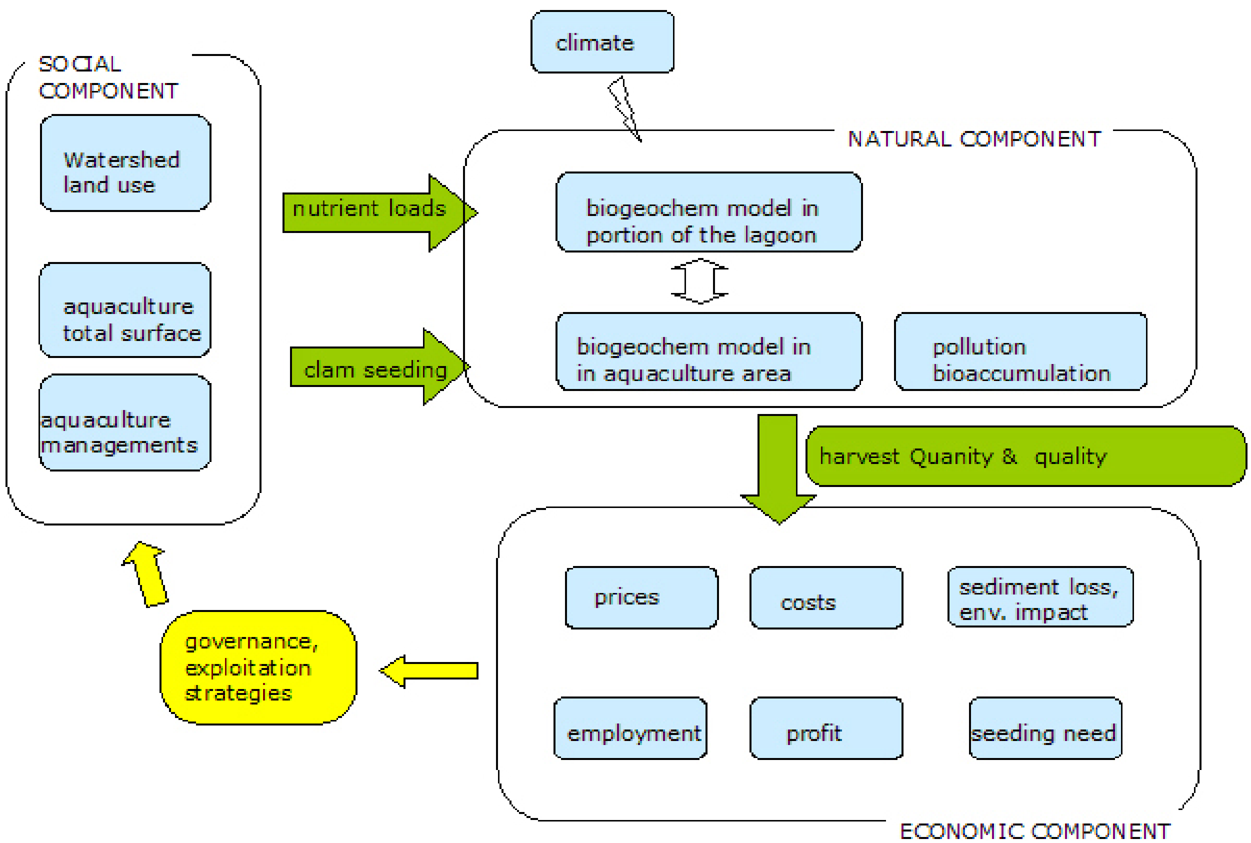


contamination data concerning three PCB congeners (PCB 105, PCB 118, and PCB 180). Sediment and water contamination input data were estimated on the basis of literature (Ciavatta et al. 2009) and site-specific measurements (Table 3; MAV-CVN 2003).

Clam growth and population dynamic model

The bioenergetic model simulates the growth of an individual clam as a function of water temperature, seston concentration, and seston energy content (Solidoro et al. 2000). According to the model, if there is no food limitation, the growth rate is limited by the metabolic processes within the clam and varies with clam size and temperature, regardless of food availability. Conversely, when the ingested food provides less energy than potentially needed, there is a food limitation. Temperature influences the rate of metabolic processes, which increase exponentially as temperature increases from lower values and approaches an optimum and then decreases down to zero when the temperature reaches an upper limit. Moreover, physiological thermal limits of anabolic and catabolic processes vary with individual clam size. The model simulates stock depletion due to natural mortality and, when present, harvesting. It simulates also the age-structured population dynamic, and the gonadal development and spawning events as function of

Fig. 3. Scheme of the integrated ecological-social-economical (ESE) model structure.



clam size and temperature regimes (Solidoro et al. 2003).

New clams are added after each spawning event (twice/year). The number of newly born clams depends on the number of adults and is modulated by a random function between 0 and one. The simulation of seed recruitment allows us to demonstrate the benefits derived from harvesting larger sized clams and thereby preserve the adult stock until the new clams are born (Appendix 3). With seed we refer here to newly born clams at the juvenile stage, settled in the sediment bottom. When we refer to hatchery or natural recruited seed we refer to juvenile clams of various sizes.

The economic model

The social and economic submodel (Fig. 3) converts the growth model results to economic data while taking into account social aspects, such as ensuring fishermen's employment, reducing health risks for clam consumers, and mitigating environmental damage. Employment is measured as the number of fishermen working on clam aquaculture. Consumer and environmental aspects have been assessed by introducing the willingness of consumers to pay for reducing the health risks linked to clam consumption (Castellini et al. 2011) whereas environmental aspects are estimated as costs for restoring the damage produced by the intensive clam harvesting tools, i.e., dredging, on the morphology of the lagoon (Orel et al. 2000). These are nonmarket values, not actually internalized as market price, but they are included in the model as public or social effects, which are helpful in policy maker decisions.

The socioeconomic variables are calculated with a daily time step and overall revenues and costs have been discounted along the whole simulation time length. The fleet size is estimated according to the

Table 3. Contamination levels in clam tissue and samples. The model is not very sensitive to the small differences in pollutants among leased areas, but it recognizes that PCB concentrations in the top sediment around industrial areas are at least an order of magnitude higher than in the rest of the lagoon.

Chemical	Field data: leased areas	Model output: leased areas	Model output: illegal fishing grounds
PCB 105	1.45×10^{-7}	3.29×10^{-7}	2.76×10^{-6}
PCB 118	5.43×10^{-7}	3.56×10^{-6}	3.65×10^{-5}
PCB 180	4.49×10^{-7}	4.06×10^{-7}	7.19×10^{-6}

number of fishing days or harvesting time (Pellizzato and Da Ros 2005). Specifically, at each time step the model calculates catches, revenues, costs, and number of harvesting vessels, whereas overall profits and fleet size are evaluated at the end of the simulation time (see details on the economic model formulations in the Appendix 4).

Endogenous prices could not be estimated because most of clam production is not exchanged on the market but goes directly from producers to retailers through cleaning clam centers (Torricelli et al 2009). In the model, prices are exogenously defined; they were calculated using a five-year time series (2005-2009) of the clam prices fixed in the wholesale market of Chioggia. We introduced in the model the average price, removing trend and cycle effects, while retaining seasonality effects. Furthermore, the model computes a premium price for selling bigger clams. The cost for cleaning clams is subtracted from the price. Because this cost is around €0.25-0.30/kg (Boatto et al. 2005), we assume a value of €0.40/kg to be conservative. The cost associated with clam aquaculture includes several components: (i) variable fishing costs, i.e., fuel and oil expenses; (ii) seeding costs; (iii) monitoring costs; (iv) license costs; and (v) fixed costs, mainly depreciation. The model calculates fixed costs at the end of the simulation according to the number of vessels and the fishing period length. Labor costs are excluded because they are difficult to define. The salary of a fisherman depends not only on fixed components but also on the gross profit, i.e., revenue minus variable costs, coming from harvesting and selling clams. The latter is variable depending on fishing and market conditions.

The model takes into account the social benefits through two components: (i) the willingness to pay for the reduction of health risk, which is included as a price change, and (ii) the environmental damage due to clam harvesting activity that may alter lagoon morphology.

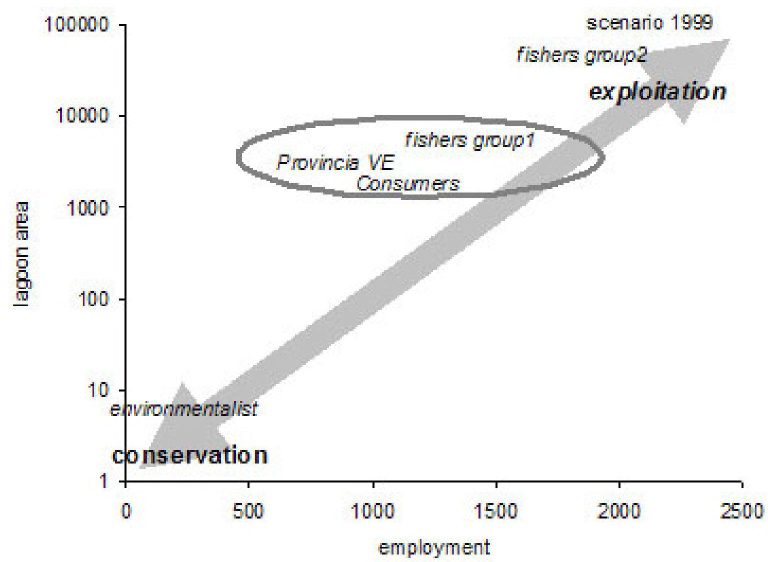
RESULTS

Identification and selection of management strategy scenarios

We selected scenarios to be compared based on stakeholder meetings, technical documents produced by local institutions (see Table 1), and GIS maps of lagoon habitats, uses, and conflicts provided by Osservatorio Naturalistico della Laguna (Fig. 4). At the two extremes of the exploitation level arrow are the “conservation scenario,” supported by some environmental groups, and the “full exploitation scenario,” suggested by the behavior of the illegal fishermen (fishers group 2). Other stakeholders suggested more intermediate scenarios in which most players were eventually able to compromise.

Based on stakeholder interactions, we assumed that the actual lagoon area devoted to clam farming (~30 km²) is acceptable under a multiuser perspective, and we made the scenarios assuming this spatial

Fig. 4. Clam resource management scenarios. Grey arrow indicates, at the two extremes, the two extreme views relative to clam harvesting: the conservation, i.e., no harvesting, and the open access. In between there is an area of alternative views, currently supported by the stakeholders, among which we made the sensitive analysis.



configuration (Fig. 5). Other criticisms raised in the stakeholder meetings were the availability and cost of clam seed and, indeed, the building of a local hatchery system has been proposed by a new project lead by the Venice Municipality. Our scenarios explore this possibility via consideration of the options of natural recruitment from the lagoon versus the use of locally hatched seed. We also included the costs of these alternatives. Other parameters considered in the definition of the scenarios included seeding size, seeding density, seeding month, and harvesting size, which are all related to aquaculture practice, and the type of lagoon area, which in turn is related to natural variability. Parameters that could not be controlled inside the analyzed system, such as climate or nutrient loads from the drainage basin, were excluded a priori. Variation related to level of harvesting technology allowed were also not considered.

However, not all possible combinations of considered parameters defined realistic, feasible, or equally important situations. Therefore, we limited the range of variation of our parameters, considering environmental and technical constraints. As an example, we fixed the seeding density to 400 ind/m^2, for the 11 mm seeding size (or to the equivalent density for the 14 mm seeding size) and we conditioned the seeding time with respect to seeding area and natural seed availability. These choices reduced the initial number (~1700) of possible scenarios to 60 combinations of seed type, seed size, harvesting size, and area type (Table 4). We considered four area types, which have been represented by using site specific biogeochemical forcing for concession areas 1, 3, 6, and 9 (Fig. 5). These areas were selected based upon the results of a previous modeling study, to introduce spatial trophic variability in the analysis (Melaku Canu et al. 2010). Scenario definition was completed by introducing the selling price, given by the market time series (www.chioggia.org/ittico/index.php), and the gross profit without labor cost, which was fixed to a starting value of €50,000/y. These parameters were common to all 60 scenarios (Table 5).

We therefore compared the results by simulating 10 years of harvesting in one hectare and exploring

Fig. 5. The Venice Lagoon and position of concession areas. Numbers 1-4 identify the simulated area types.

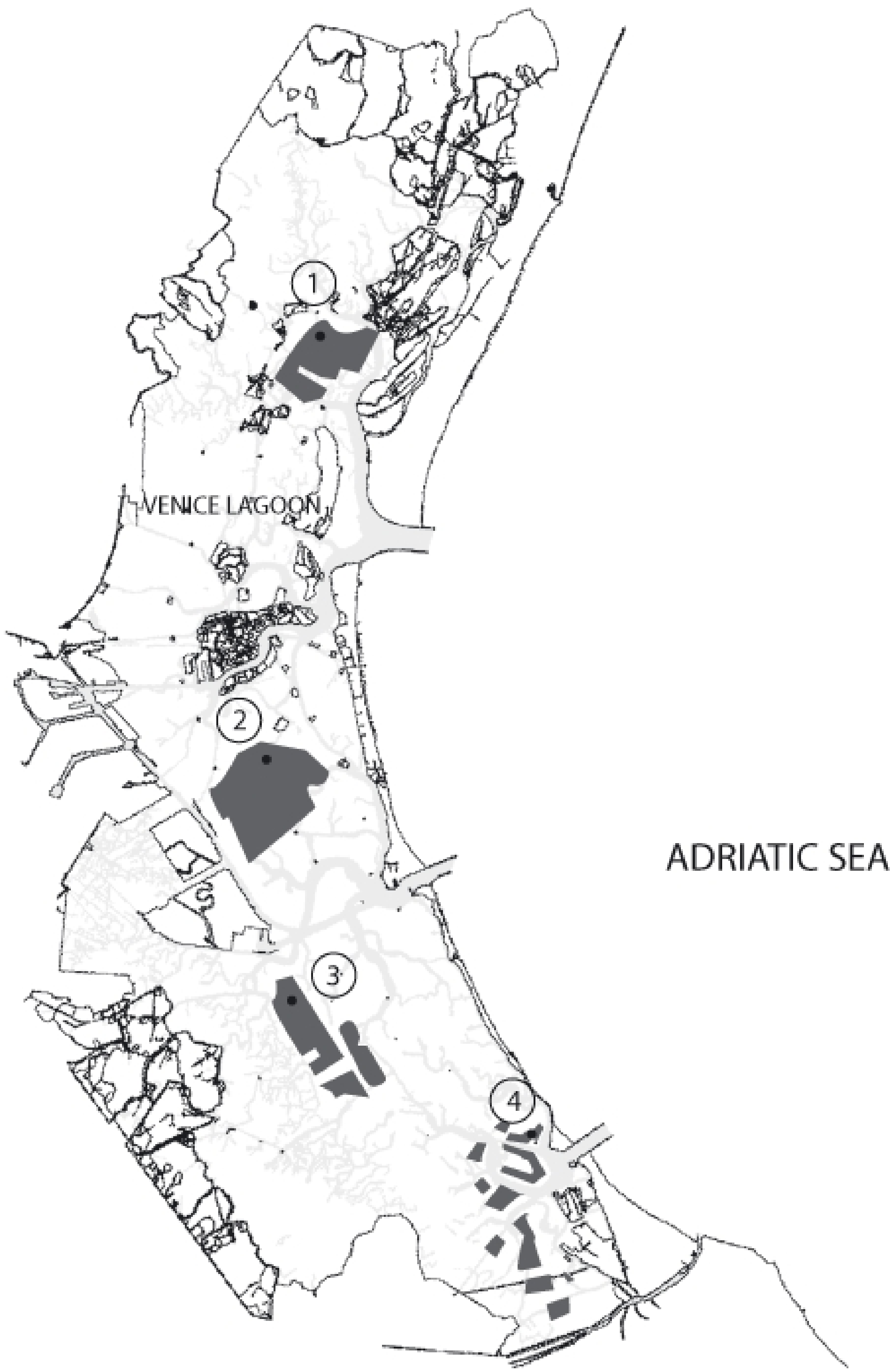


Table 4. Description of the (15) scenarios simulated for each of the four lagoon area types.

	Harvesting size		
Seeding size and type	size25	size27	size30
11 mm Natural	11NatH25	11NatH27	11NatH30
11 mm Hatchery	11hatchH25	11hatchH27	11hatchH30
14 mm Natural	14NatH25	14NatH27	14NatH30
14 mm Hatchery	14HatchH25	14HatchH27	14HatchH30
14 mm Local Hatchery	14lHH25	14lHH27	14lHH30

harvest, productivity, relative impacts on the lagoon (externalities), and payback (profits before paying employees). Extending the results to the whole clam farming surface, we estimated the total Venice Lagoon clam productivity and employment possibilities.

Simulation results

The set of simulations indicates that profit, productivity, and employment vary significantly in response to different exploitation strategies. The bioaccumulation model confirms that the production of the selected area meets quality standards, and therefore, the premium price has been introduced in our results to take into account consumer preference. The average sensitivity of profit to the change of parameters has been evaluated by comparing the dispersion index around the median value of profits (Table 6). The sensitivity to seeding source is very high, 72%, followed by the sensitivity to seeding month, 47%, and to harvest size, 31%. Sensitivities to seed size and area type are less relevant, with a value of, respectively, 9% and 10%.

Comparison of the results of final scenarios selection (Table 7) confirms that the highest profit values are reached when harvesting larger individuals and using natural seed. The set of simulations indicates that the amount of seed needed for the whole clam farming area varies between 2300 and 7800 tons/y. However the natural seed availability is estimated to be lower; GRAL 2009 reports values as low as 720 and 1200 tons for years 2006 and 2008. Therefore, even assuming that these values are underestimated, we excluded from our results those scenarios requiring more than 3000 tons/year of natural seed that are considered to be unsustainable. Similarly, we excluded scenarios requiring hatchery seeding exceeding 4000 tons/y. A posteriori, we observed that, by doing this, we also excluded cases presenting productivity higher than 1.6 kg/m²/y, which was the production carrying capacity computed by Melaku Canu et al. (2010). In fact, the productivity of the remaining 16 scenarios ranged between 1.16 and 1.36 kg/m²/y. It can also be observed that the 14 mm seed option is also filtered out, along with strategies based on a local hatchery. The computed average employment is of 1297 farmers, with a minimum of 569 in the worst case (11 mm hatched seeds grown in area type 1 and harvested at 25 mm) and of 1873 in the best case (11 mm natural seeds grown in area type 2 and harvested at 27 mm).

However, to suggest a resilient social carrying capacity, we should also take into account some uncertainty related to variations that cannot be controlled by policy makers, such as fluctuations in prices or in nature. We therefore performed an additional set of simulations by reducing the average clam selling price by €1/kg and by €2/kg; we also increased the natural mortality by 20% as a proxy of a natural condition in a 'bad' year. Sensitivity to price is very high, with an average decrease over the 60 original scenarios of about 59%

Table 5. Parameters taken into consideration in the definition of the scenarios.

Seeding type	Seeding month	Seeding size	Seeding density	Harvesting size	Area type
Natural	Jan to Dec	11, 14 mm	300 - 400 ind/m²	25, 27, 30 mm	1-2-3-4
Hatchery	Jan to Dec	11, 14 mm	300 - 400 ind/m²	25, 27, 30 mm	1-2-3-4
Internal hatchery	Jan to Dec	14 mm	300 - 400 ind/m²	25, 27, 30 mm	1-2-3-4

(€-1/kg scenario) and 117% (€-2/kg scenario) in profit. Incidentally, this finding alone indicates that management strategies and economic constraints can be more relevant than trophic variability. Increasing the clam mortality model parameter of 20% and 50% caused a reduction in productivity of 10% and 22%, respectively. The worst-case scenario, in which the selling price is around €1.50/kg and mortality is increased, presents a substantial decrease of profits. Under these very unfavorable conditions, employment is no higher than 470 people (Table 8).

Externalities are lowest when harvesting the 30 mm clams and highest, about 40% higher, when harvesting at 25 mm. This is because of the amount of harvesting that occurs in the field over the 10 years of our simulation, which is lower when the seed is smaller and/or when the harvesting size is larger.

Finally, we simulated the local natural seed produced inside the clam field, varying harvesting size among 25, 27, or 30 mm. This estimate is approximate; the parameter is difficult to model because of random events such as predation and hydrodynamics that influence the actual recruitment (Hunt 2004, Ripley and Caswell 2006, Dang et al. 2010). We therefore combined deterministic formulation, which is based on biological observations related to temperature and gonadal development (Paesanti and Pellizzato 2000, Solidoro et al. 2000), and a random function, aiming to include the natural randomness. This value was not directly included in the profit analysis, but it is nevertheless a factor that should be considered in management choices. Profits related to natural recruitment are 60% higher when harvesting at 30 mm in comparison to 25 mm.

Upscaling at the lagoon level: confronting extreme and realistic scenarios

In the previous section, we explored the implications of a number of feasible strategies of clam exploitation in one hectare of lagoon area for 10 years. In this section we combine the simulated profits, productivities, and social effects of these different management strategies for the assessment of consequences of implementation of alternative management scenarios at the whole lagoon level.

Table 9 summarizes the comparisons among five alternative scenarios (see also Fig 4): the full exploitation scenario, in which figures are inferred from data and estimates from 1999, a total conservation scenario, and three alternative management scenarios.

According to Orel et al. (2000), fishermen harvested a surface area of 40,500 ha in 1999 that, considering sediment resuspension and loss, induced externalities estimated as €12.15 million/year. Assuming an estimated production in 1998 of 40,000 tons, corresponding to €64 million when assuming a price of €2/kg, the share of environmental damage is equal to 19% of production value. ScenMix1 is a scenario constructed with the assumption that the seed comes from natural nurseries (800 tons) and from foreign hatcheries (1600 tons). Over 10 years of simulations, six yields are produced, seeded at the 11 mm size and harvested at the 30 mm size. The externalities of ScenMix1 are computed by summing the externalities generated by clam harvesting in the 3000 ha of lagoon surface plus the externalities generated by seed dredging in 600 ha of lagoon surface nursery area (6 harvests in 10 years). Under this scenario, the total area devoted exclusively to clam aquaculture is almost the value

Table 6. Model sensitivity computed by measuring the dispersion index of the model scenario outputs (profits) and varying input parameters (seeding size and type, area type, harvesting size, seeding month).

Dispersion index on profit	Seed size (11/14 mm)	Seed source (HI, Hatch, Nat)	Harvest size (25, 27, 30)	Area type (1,2,3,4)	Seed month (Jan to Dec)
(max-min)/median	9%	72%	31%	10%	47%

that most of the stakeholders agree upon and the externalities are around 1.5% of revenue, lower than in the ‘full exploitation scenario.’ ScenNat is based only on natural seed: 1600 tons of seed are assumed to be collected from 1800 ha of natural nursery area, whereas ScenMix2 simulates both the increase of the natural nursery area up to 1200 ha and the seeding of 1600 tons of hatchery seed. For comparison, the model computes profits and externalities using the same unit value but with a higher selling price for the ScenMix1, ScenNat, and ScenMix2 scenarios to take into account consumer quality preference. Assuming an individual annual revenue of €50,000, we compute the maximum sustainable number of fishermen for the three scenarios ScenMix1, ScenNat, and ScenMix2 as 935, 1288, and 1111 individuals, respectively. To take into account uncertainties due to natural and price variability, this value can be conservatively reduced to ~800, which is lower than the MAV-CVN estimate of total number of clam workers in 2008, but not far from the current figure of 742 regular clam farmers, according to GRAL (www.gral.venezia.it).

DISCUSSION

Our purpose was to explore the ESE system of clam farming in the Venice Lagoon, following the SAF, demonstrating the feasibility and advantages of sustainable management. Clearly, feedbacks exist between socioeconomic and environmental components. The model describes in a quantitative way the relationships and feedbacks between the natural environment, the clam stocks, and the choices of humans, enabling the stakeholders to better understand and to compare consequences of alternative scenarios, therefore supporting management planning. Consumer preferences, evaluated by the questionnaire (Appendix 1), have been taken into account in the scenario analysis by simulating changes in prices to reflect consumers’ willingness to pay for a healthier product. Results are highly sensitive to price changes thus indicating the implementation of a quality certification system as a viable support toward market resilience.

Specific modules making up the integrated model provide, in general, only a simplified description of reality. However, this simplification is unavoidable and possibly even useful when dealing with a high level of complexity, such as that of the governance of an ecological-social-economical system. Our approach is, in fact, not based on the maximization of production alone; it considers a balance among different uses, demands, and natural properties and vocations. Therefore, a multidisciplinary, holistic, systemic view is required, whose coupling with very accurate descriptions of selected processes is difficult, possibly useless, and potentially distracting.

Our model suggests that a properly managed aquaculture system that uses about 3000 ha of lagoon and employs about 800 full-time people leads to a sustainable situation that is accepted by most stakeholders and, from a socioeconomic viewpoint, is not much different from the current status. Uncertainty analysis suggests that this configuration is sustainable even when adopting a conservative, precautionary approach. We can therefore speculate that the current problems are at least partially due to insufficient implementation of appropriate management policy and persistence of illegal fishing.

Environmental externalities, even though not explicitly internalized in the economic model, have been quantified to show the relative impacts among the selected harvesting scenarios (Fig. 6). Results indicate that the most sustainable management

Table 7. Selected reference scenario results (rows), changing model parameters (columns 1-4). Columns 5-10: scenario results using selected indicators (profits, externalities, harvest, productivity, maximum employment, and seeding needs).

Seed size	Source	Area	Harv size	Profits	Externalities	Harvest	Productivity	Max employment (lagoon)	Seeding needs (lagoon)
mm	*code*	*type*	*mm*	*euro/ha/y*	*euro/ha/y*	*kg/ha*	*kg/m²*	*number*	*ton/year*
11	Nat	2	27	33,453	596	13,584	1.36	1873	3101
11	Nat	4	27	33,364	596	13,801	1.38	1868	3101
11	Nat	4	30	31,334	381	13,192	1.32	1755	2326
11	Nat	2	30	30,905	381	13,149	1.31	1731	2326
11	Nat	1	30	30,854	381	12,497	1.25	1728	2326
11	Nat	3	30	30,166	381	12,747	1.27	1689	2326
11	Nat	3	27	28,985	483	11,784	1.18	1623	2713
11	Nat	1	27	27,743	483	11,613	1.16	1554	2713
11	Hatch	4	30	21,796	180	13,168	1.32	1221	2326
11	Hatch	2	30	21,433	180	12,983	1.30	1200	2326
11	Hatch	3	30	20,750	180	12,698	1.27	1162	2326
11	Hatch	1	30	18,976	180	12,458	1.25	1063	2326
11	Hatch	1	27	18,238	240	13,317	1.33	1021	3101
11	Hatch	2	27	17,908	240	13,700	1.37	1003	3101
11	Hatch	4	27	17,075	240	13,542	1.35	956	3101
11	Hatch	3	27	16,902	240	13,251	1.33	947	3101

strategy is also the one with the longest harvesting cycles and the highest uncertainty. The best scenarios could be operated by farmers only if an agreement on practices can be achieved. This requires the promotion of education, vision sharing, self-enforcement, and tools for risk reduction, such as building a local hatchery. In addition, as also emerged from stakeholder interactions, we suggest the integration of other activities, such as fishing-tourism, and the promotion of marketing solutions, such as traceability and transformation (Nunes et al. 2008). In summary, the promotion of fishermen participation in a diversification system will achieve a higher level of resilience and reduce some of the environmental impacts.

However, our experience also shows that although it is relatively easy to share information, data, and ideas among stakeholders, it is more difficult to really influence the management process. The level of stakeholder involvement was not very high because major clam fishing governance structure was going through an internal reorganization process, and fishermen did not see an immediate

Table 8. Sensitivity analysis to reduced price -2 euro. Selected scenarios (rows) changing model parameters (columns 1-4). Columns 5-10: scenario results using selected indicators (profits, externalities, harvest, productivity, maximum employment, and seeding needs).

Seed size	Source	Area	Harv size	Profits	Externalities	Harvest	Productivity	Employment (Lagoon)	Seeding needs (Lagoon)
mm	*code*	*type*	*mm*	*euro/ha/y*	*euro/ha/y*	*kg/ha*	*kg/m²*	*number*	*ton/year*
11	Nat	1	30	8398	381	12,497	1.25	470	2326
11	Nat	3	27	7669	483	11,784	1.18	429	2713
11	Nat	4	30	7501	381	13,192	1.32	420	2326
11	Nat	2	30	7157	381	13,149	1.31	401	2326
11	Nat	3	30	7150	381	12,747	1.27	400	2326
11	Nat	1	27	6765	483	11,613	1.16	379	2713
11	Nat	4	25	2694	857	14,299	1.43	151	3876
11	Hatch	1	25	-	300	13,650	1.36	-	3876
11	Hatch	2	25	-	300	14,251	1.43	-	3876
11	Hatch	3	25	-	300	13,918	1.39	-	3876
11	Hatch	4	25	-	300	14,295	1.43	-	3876
11	Hatch	4	30	-	180	13,168	1.32	-	2326
11	Hatch	2	30	-	180	12,983	1.30	-	2326
11	Hatch	3	30	-	180	12,698	1.27	-	2326
11	Hatch	1	30	-	180	12,458	1.25	-	2326
11	Hatch	1	27	-	240	13,317	1.33	-	3101
11	Hatch	2	27	-	240	13,700	1.37	-	3101
11	Hatch	3	27	-	240	13,251	1.33	-	3101

payback in participation. Furthermore, because of its dimension, complexity, and history, the present day Venice Lagoon clam system shows a substantial inertia against adaptations (D. Melaku Canu and C. Solidoro, *unpublished manuscript*). It was possible to engage a group of stakeholders in the identification of model structures and management scenarios. This favored stakeholder interactions, enabling different groups to consider different perspectives, therefore promoting common language and holistic views. Possibly this will initiate an iterative process with engagement of other stakeholders that will lead to the support of sustainable management. On the other hand it is increasingly recognized that scientific knowledge alone, although a prerequisite for informed management and a crucial component of decision support systems, is not sufficient to prompt efficient

Table 9. Comparison among alternative clam exploitation scenario, as set by Figure 4. The extreme scenarios, represented by full exploitation scenario (data and estimates from 1999) and no exploitation scenario (†data, ‡estimates), are compared with three intermediate scenarios: ScenMix1, ScenNat, ScenMix2, assuming a revenue of 50,000 euro/year/worker. Surface and employments parameters have been set at first, productivity, revenue and externalities have been computed using modeling results.

parameters/scenarios	1999	ScenMix1	ScenNat	ScenMix2	Conservation
boats	1400	400	400		0
workers	2500†	935‡	1288‡	1111‡	0
seeding tons (Natural)[tons]	0	800	2400	1600	0
Seeding tons (Hatchery) [tons]	0	1600		800	0
global surface fished/year [ha]	40,500	2160	2880	2520	0
sediment loss (from Orel et al. 2000) [m³]	405,000	21,600	27,600	21,600	0
Environ. externalities (1999 value) [million euro]	12.15	1.07	1.10	1.36	0
production [tons/year]	40,000	37,132	37,266	37,199	0
profits‡(20% premium price quality) [million euro]	64	47	64	56	0
% externalities	19%	1.5%	1.7%	1.6%	0

implementation of any policy (Daw and Gray 2005, Ostrom 2009) especially in large and complex systems. Finally, by providing concrete basis for discussion, and indicating the existence of viable solutions, our results also elucidate and emphasize the need to address issues related to the institutional structure and its role.

CONCLUSION

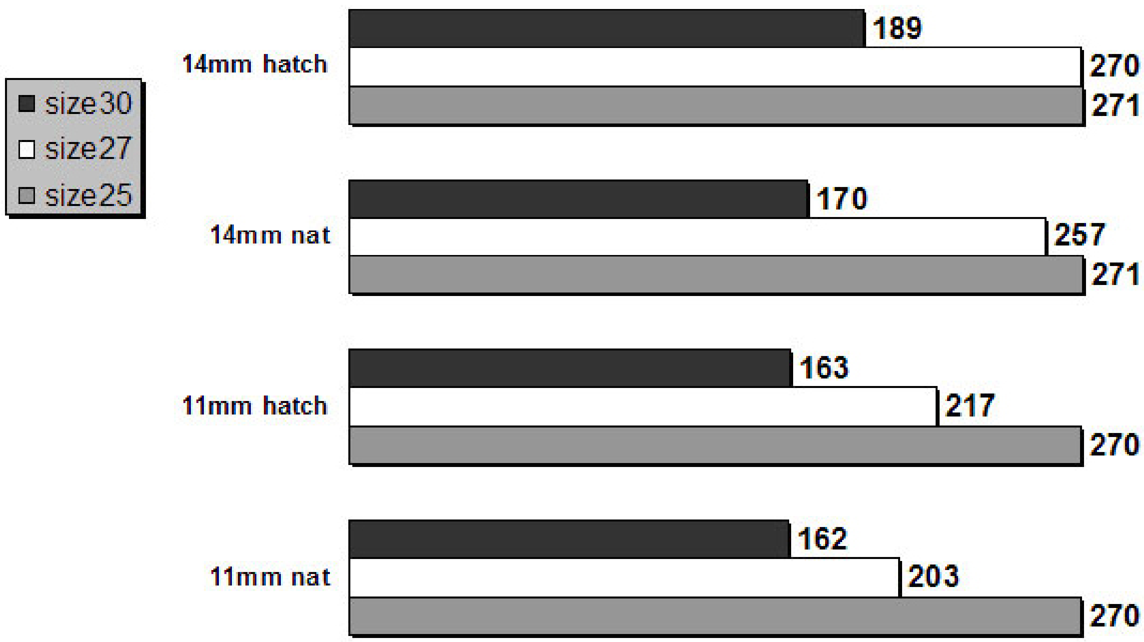
In this work, we attempted to integrate the existing knowledge, scientific findings, social experiences, and awareness to address the social-ecological carrying capacity of the clam exploitation system in the Venice Lagoon. We developed and applied an integrated model that was also based on repeated interactions with different stakeholders, and used it to compare effects on the ecological, social, and economical components of implementation of alternative management strategies.

In closing, we would like to reiterate our major conclusions:

1. The integrated model suggests the sustainability of a properly managed aquaculture system that uses about 3000 ha of lagoon and employs about 800 full-time people. From an economic perspective, this situation would not be very different from the current one, but would have less impact from an ecological perspective, and socially, would be more stable.

2. The most sustainable management strategy is also the one with the longest harvesting cycles and the highest uncertainty. This further stresses the need to promote clam farmers' cohesion and self-enforcement, along with their inclusion in the decision making process.

Fig. 6. Externalities [euro/ha/year] computed varying seeding and harvesting size.



3. Model results suggest that productivity inefficiencies are more related to management choices and seed scarcity than to environmental constraints.

4. Models show a high range of uncertainty that depends in part on the model parameterization but also on the randomness of natural/biological processes, mainly predation and mortality, and to economic factors such as price and consumer preferences. This suggests using a precautionary approach when addressing the social carrying capacity.

5. Based on stakeholder meetings and other studies, we underline the need for diversification, i.e. transformation, fishing-tourism, and hatchering, as well as quality control, such as traceability, as strategies to reduce risk.

6. Efficient implementation of scientifically sound management policies cannot be prompted by scientific knowledge alone but requires proper governance actions that need proper time to be implemented. Stakeholder engagement, in model development and scenario analysis, favors interaction and vision sharing, thus promoting better management.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/vol16/iss3/art26/responses/

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APPENDIX 1. Consumer Survey Results

We conducted a survey among Confconsumatori (Consumer Association members). About 80% of the people interviewed normally buy fish at a frequency greater than 4 times per month (40%). 40% of them buy seafood at the fish market, 30% at the corner shop, and 20% at the supermarket. The preference are for sea-fish (50%) over farmed fish (14%) and Italian fish (60%) over foreign fish (4%). Mussels is the preferred seafood.
In the Venice area, 77% of respondents consume clams monthly and they are satisfied with the product purchased (86%) and consider it safe (64%). The safety of the product is associated with the cleanliness of the place of purchase and trust in the vendor response.
In fact, 77% of the people interviewed were not aware of health legislation relating to the consumption of seafood products.
Approximately 86% would pay a higher price, by about 10%, to have a product with a quality certification.

Regarding environmental issues associated with clam collection in the Lagoon of Venice, 64% believe that clam fishing create environmental problems, especially those related to the reduction of biodiversity and erosion of the seabed, whereas a small group of people think that it has effects on the water quality and turbidity. From the social point of view, 95% considered the illegal fishing of clams a significant problem that must be solved, but at the same time many (about 77%) believes it is important to protect clam fishermen and see this since activity important for employment reasons and for its traditional roots.

Questions									notes
Do you buy fish usually?	yes 81%	no 14%							
How many times per week?	1 59%	1 to 3 18%							
In a month?	1 14%	1 to 3 14%	4 to 10 41%	> 10					
Where do you buy your fish?	market 41%		supermarket 18%		Corner shop 32%				
Which kind of fish do you buy more?	Fish form aquaculture 14%		Open sea fish 50%		shellfish 18%	Mollusca 50%	Italian fish 59%	Foreign fish 4%	
Are you used to eat clams?	yes 77%	no 23%	Every week 9%		Every month 59%				Why not? - Uncertain origin - don’t like - buy only sea clams, don’t trust lagoon clams
In general, are you satisfied about the product you buy?	yes 86%	no							- trust seller - freshness - good value for money
When do you usually eat clams?	Holiday time 27%		Normally 54%						
Do you think that the product you buy it is safe and of a good quality?	yes 64%	no 14%	Why yes - the cleanliness of the shop - trust seller			Why not - illegal fishing -no check on the origin of the product -polluted environment			
Are you aware about the sanitary directive regarding selling/eating clams?	yes 14%	no C							
Are you willing to pay more for a product with a quality certificate?	yes 86%	no 9%	1% 9%		5% 9%	10% 23%	20% 14%	Why yes -more safety	Why not -the product must be in any case of good quality -the quality certificate doesn’t imply greater safety
If the product had the certification would you consume it most often?	yes 36%	no 59%							

Are you aware about the environmental, social, economic issue related to clam fishing in the Venice Lagoon?	Yes 50%	No 45%	I don’t know 4%					
Does clams harvesting in the Lagoon of Venice induce environmental problems, in your opinion?	yes 64%		Water quality 14%	turbidity 18%	Loss biodiversity 55%	erosion 45%		
Are you aware about the differences between harvested and farmed clams ?	yes 36%	no 59%						
Do you thing that the clams you buy are farmed clams?	yes 50%	No 27%						
Do you thing that the clams you buy come from an aquaculture area?	Yes 95%	no						
To your point of view, does clam fishing damage the Venice Lagoon?	no 9%		A little 23%	enough 36%	A lot 18%	completely 9%		
According to you, did the last five years management reduced the environmental damage in the Lagoon of Venice?	no 27%		A little 27%	enough 23%	A lot	completely		
According to you, the presence of fishermen of clams in the Lagoon of Venice should be protected?	yes 77%		No 14%	Why yes- tradition -Employment -Required fishing in areas under concession		Why Not: - all fishermen come from Pellestrina -the environmental damage is much more than the economic intake -Natural-habitat restoration		

Table A1. Results of the questionnaire submitted to the association of consumers in order to explore consumer perception of clam farming issu

APPENDIX 2. Bioaccumulation model

The bioaccumulation model allows the estimation of the lipophilic contaminants concentration, such as PCBs and dioxins, in clam tissues on the basis of site specific data concerning the contamination of water and sediment, the physico-chemical properties of the toxicants and the physiology and ecology of the target organisms. Model equations are based on the more general food-web bioaccumulation models already cited in the main text. The model mass-balance equation Eq. [A.1] at steady-state reads as:

$$C_{B,i} = \left(k_1 C_{WR} + k_D C_{D,i}\right) / \left(k_2 + k_E + k_G + k_M\right) \quad [A.1]$$

where $C_{B,i}$ is the concentration of the toxicant in the organism [g/kg]. On the right hand side, the numerator quantifies the rate of uptake of the toxicant, due to two processes: the physical contact with the dissolved chemical (k_1C_{WR}) and the diet ($k_DC_{D,i}$). The denominator quantifies the loss and dilution rates through respiration (k_2), faeces production (k_E), growth (k_G) and metabolic processes (k_M). The set of model equation, the functional expressions and parameters are described in detail in the Table below.

The steady-state assumption implies that organisms are exposed to the same toxicant concentration throughout their life cycle: such hypothesis, though questionable, is likely to be satisfied in shallow water environments, where the concentration in top sediment largely determine the dissolved one, through partition processes. Since sediment concentration changes rather slowly, benthic filter feeders, such as *Ruditapes philippinarum,* are exposed to a roughly constant flux of toxicant.

$$C_{WR} = m_O C_{WD,O} + m_P C_{WD,S} \quad [A.2]$$

$$C_{WD,O} = \frac{C_{WT,O}}{\left(1 + a_{POC} k_{OW} POC + a_{DOC} k_{OW} DOC\right)} \quad [A.3]$$

$$C_{WD,S} = \frac{C_S}{OC_S \alpha_{OC} k_{OW} \delta_S} \quad [A.4]$$

$$C_{D,i} = C_{WT,O} k_{PW} \quad [A.5]$$

$$Log\, k_{OW}\left(T_W\right) = Log\, k_{OW,25} + \frac{\Delta H_{OW}}{R \ln(10)}\left(\frac{1}{298.15} - \frac{1}{T_W}\right) \quad [A.6]$$

$$k_1 = E_W G_v / W_b \quad [A.7]$$

$$E_W = \left(1.85 + \left(155 / k_{OW}\right)\right)^{-1} \quad [A.8]$$

$$k_D = E_D G_D / W_B \quad [A.9]$$

$$E_D = \left(3.0 \cdot 10^{-7} k_{OW} + 2.0\right)^{-1} \quad [A.10]$$

$$G_D = G_v c_{sj} \sigma \quad [A.11]$$

$$k_2 = k_1 / k_{BW} \quad [A.12]$$

$$k_E = G_F E_D k_{GB} / W_B \quad [A.13]$$

$$G_F = \left[\left(1 - \varepsilon_L\right) v_{LD} + \left(1 - \varepsilon_N\right) v_{ND} + \left(1 - \varepsilon_W\right) v_{WD}\right] G_D \quad [A.14]$$

$$k_{PW} = v_{LP} k_{OW} + 0.35 v_{NP} k_{OW} + v_{WP} \quad [A.15]$$

Table A.1. List of Equations of the bioaccumulation model.

Name	**Unit**	**Type**	**Description**
$C_{B,i}$	[g kg_{ww}^{-1}]	State variable	concentration of the i-chemical in *Tapes philippinarum* tissues

C_{WR}	[g L^{-1}]	Forcing function	dissolved chemical concentration
W_b	[kg_{ww}]	Parameter	*Tapes philippinarum* wet weight
$C_{WD,O}$	[g L^{-1}]	Forcing function	concentration of the i-chemical dissolved in water column
$C_{WD,S}$	[g L^{-1}]	Forcing function	concentration of the i-chemical dissolved in sediment-associated pore water
$C_{WT,O}$	[g L^{-1}]	Forcing function	total concentration of the i-chemical in water
$C_{D,i}$	[g kg_{ww}^{-1}]	Forcing function	concentration of the i-chemical in the diet
k_1	[L kg^{-1} d^{-1}]	parameter	aqueous uptake clearance Rate
K_D	[kg kg^{-1} d^{-1}]	parameter	dietary uptake clearance rate
k_2	[d^{-1}]	parameter	respiration rate
k_E	[d^{-1}]	parameter	Faecal elimination rate
k_G	[d^{-1}]	parameter	growth dilution rate
k_M	[d^{-1}]	parameter	biotransformation rate
k_{OW}	[-]	parameter	octanol-water partitioning constant of the i-chemical
k_{PW}	[-]	parameter	phytoplankton-water partition coefficient
G_v	[L d^{-1}]	parameter	clearance rate
E_W	[-]	parameter	chemical uptake efficiency
E_D	[-]	parameter	chemical transfer efficiency
C_s	[g kg^{-1}]	Forcing function	chemical concentration in the sediment
σ	[-]	parameter	absorption efficiency
k_{BW}	[-]	parameter	biota-water partition coefficient
ε_L	[-]	parameter	dietary assimilation efficiency of lipid
ε_N	[-]	parameter	dietary assimilation efficiency of NLOM
ε_W	[-]	parameter	dietary assimilation efficiency of water
ν_{LD}	[-]	parameter	content of lipid in diet
ν_{ND}	[-]	parameter	content of NLOM in diet
ν_{WD}	[-]	parameter	water content of diet
G_F	[kg_{faeces} $kg_{individual}^{-1}$ d^{-1}]	parameter	faecal egestion rate
k_{GB}	[-]	parameter	partition coeff. of the chemical between the GIT and the organism
m_O	[-]	parameter	fraction of the respiratory ventilation that involves overlaying water
m_P	[-]	parameter	fraction of the respiratory ventilation that involves pore water
OC_S	[-]	parameter	organic carbon fraction of the sediment
α_{OC}	[-]	parameter	ratio between the sorption capacity of the organic carbon and that of octanol
δ_S	[kg L^{-1}]	parameter	sediment density

Table A.2. List of variable, forcing and parameters of the bioaccumulation model

APPENDIX 3. Clam population decay

This module computes a general first order decay rate [A.16] for the clam population due to natural mortality and harvesting, when it occurs The *d* parameter was computed by fitting the experimental data with the polynomial regression see Fig. A.1
Data were analysed to find the best regression using the entire data set, and a bootstrap analysis was also performed. regression results are shown in Fig A.1.

$$\frac{dNi}{dt} = d * Ni \qquad [A.16]$$

The *d* parameter was computed by fitting the experimental data with a polynomial regression:
Data were analysed to find the best regression using the entire data set, and a bootstrap analysis was also performed.
The equation results are as follows:
a1 = 0.0126
a2 = -0.2876
a3 = 2.6583

$$dmonth = 0.0126\mathrm{T}^2 - 0.2876 \times \mathrm{T} + 2.6583 \qquad [A.17]$$

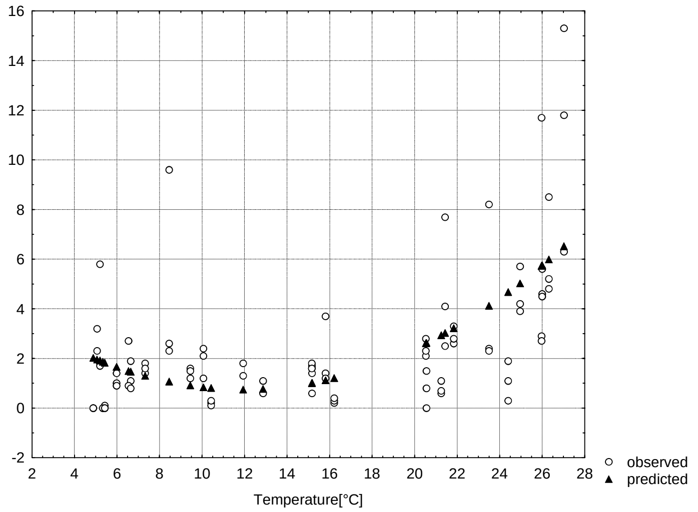

Fig. A.1 Regression results, (left) polynomial regression of the data set.

APPENDIX 4. Economic Model

Starting from the general equation:

$$v_t * cpue * day_t = s_t * a_t \quad [A.18]$$

where v_t is the number of vessels fishing each day, *cpue* (catches per unit effort) represents the volume of clams (kilos/day) caught by each vessel (Pellizzato and Da Ros 2005, Nunes et al. 2008) and is assumed to be a stochastic variable normally distributed as N~(250,10), day_t is a normalisation parameter, a_t is the area ready to be harvested (m^2) and s_t is the daily stock (kg/m^2) that is found by multiplying the number of clams per square meter (n_t) by the corresponding weight (w_t): $s_t = n_t * w_t$.

1) Vessels, catches and fishing effort

The number of vessels fishing each day, v_t, is calculated as:

$$v_t = \frac{s_t * a_t}{cpue * day_t} \quad [A.19]$$

The volume of clams harvested daily, q_t, is found as:

$$q_t = cpue * v_t \quad [A.20]$$

The daily effort, e_t (area fished every day), is calculated as:

$$e_t = \frac{q_t}{s_t} \quad [A.21]$$

2) Fleet size

The fleet size is defined as the ratio between total vessels and the average fishing days (*fd*) (160 days/vessel) (Pellizzato and Da Ros 2005):

$$F = \frac{\sum_{t=1}^{T} v_t}{fd} \quad [A.22]$$

3) Revenues and costs

The daily revenue is defined as:

$$R_t = [P_t(\alpha,\beta,\delta,\lambda) - Cc] * q_t \quad [A.23]$$

where P_t is a function of the average clam price (α), seasonality effect (β), clam selling size (δ) (Gral 2006), and the premium price to increase shellfish safety (λ) (Mauracher et al 2010), while *Cc* is the cost for cleaning clams (Boatto et al. 2005).

The daily cost is defined as:

$$C_t = Vc_t + Jc_t + Mc_t + Lc_t + Fx \quad [A.24]$$

where Vc_t ,the daily variable fishing cost, is found as:

$$Vc_t = \mathrm{v}c_t * v_t \quad [A.25]$$

where vc_t is the average fishing cost (€/day) per vessel and includes mainly fuel expenses.

Jc_t ,seeding costs, is specified as:

$Jc_t = Jp(\xi,\vartheta) * d * A$ [A.26]

where juvenile price (*Jp*) is a function of the seeding size (ξ) and the nursery type (ϑ) (natural or reared) (Gral 2006), *d* represents the number of clams sown per square meter and *A* is the total area sown.

Mc_t ,daily monitoring cost, is defined as:

$Mc_t = m_y * (A/360)$ [A.27]

where m_y is the annual monitoring cost (ha/year).

Lc_t ,the license cost, is defined as:

$Lc_t = lc_y *(A/360)$ [A.28]

where lc_y is the license costs (ha/year) (Torricelli et al. 2009)

Fx, the fixed cost, is calculated at the end of the simulation. In particular, the estimated annual fixed cost *Fxy* (Orel et al. 2000, Torricelli et al. 2009) is converted into a daily cost that is then multiplied by the period of simulation (T) (expressed in days) and fleet size :

$$Fx = \frac{Fx_y}{360} * T * F \qquad [A.29]$$

4) Environmental damage

The environmental damage associated with clam harvesting is assessed as:

$Ex_t = ex * e_t$ [A.30]

where *ex* represents the value of the sediment losses (euro/m^2) (Orel et al. 2000) and e_t is the daily effort.

5) Profits

i) The daily profit is found as daily revenue minus daily costs:

$\pi_t = R_t - C_t - Ex_t$ [A.31]

where Ex_t is a scenario variable.

ii) The overall net profit is the sum of the discounted daily profits:

$$\Pi = \sum_{t=1}^{T} \frac{\pi_t}{(1+i)^t} \qquad [A.32]$$

iii) The profit per vessel is the ratio of total net profit and fleet size:

$$\Pi_v = \frac{\Pi}{F} \qquad [A.33]$$

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