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MONOGRAPH

Analysis of clam farming scenarios in the Sacca di Goro lagoon

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Abstract

1 - Different scenarios and their prioritization were identified for the Sacca di Goro (Adriatic Sea, Northern Italy), an eutrophic lagoon which is exploited with extensive clam farming activities. A preliminary scenario assessment was investigated with qualitative modelling. Economic and environmental variables were accommodated in a comprehensive model of the lagoon that describes major interactions between selected compartments. This kind of analysis is specially suited for systems that are partially specified. In a second step, we addressed the first priority scenario identified by end-users and which concerns clam farming activities in the lagoon. This scenario was analysed using a quantitative approach based on a 3D integrated hydrodynamic-biogeochemical model. Such approach allowed the assessment of the implications of an increase in the clam farming area.

2 - The first results seems to indicate that a further increase of clam farming areas (or a more intense exploitation) inside the Sacca di Goro lagoon would increase the risk of anoxia and the vulnerability of clam farming to *Ulva* blooms. On the contrary, an increase in the exploitation area outside the lagoon will increase the average productivity and maintain constant the risks of anoxia and the vulnerability to *Ulva* blooms. Furthermore, the cost of measures taken by the local and regional authorities for the lagoon management and to control nuisance macroalgal blooms are potentially compensated by the increase in clams production predicted by the model.

3 - The focus on clam farming provides only a partial view of a more complex system which composes by agriculture, urban, touristic areas, and natural sites and is under the influence of climate changes. However, such scenarios constitute only the first stage in the procedure of overall lagoon scenario analysis, and a second iteration is necessary to define the main constraints and boundaries, as well as to incorporate the economic evaluation and social implications of the different options.

Keywords: Clam farming, DPSIR, Qualitative models, Ecological models, Ulva, Environmental impact

Introduction

Management of coastal lagoons is a complex task requiring interdisciplinary research and active interaction with the end-users and stake-holders. The successful management of human activities and natural resources in such complex ecosystems requires the integration of information provided by geomorphology, hydrology, biology and ecology, combined with the compliance of environmental policies and socio-economic development plans. In this sense, socio-economic analysis assumes great importance, especially where various kinds of anthropogenic pressures (aquaculture, fishery, tourism, etc.) are sources of conflicts among different users. Integrated tools, such as Decision Support Systems (DSS) based on multi-criteria approaches, may support decision-making by end-users. A pilot study was undertaken within the European project DITTY (Development of an Information Technology Tool for the Management of European Southern Lagoons under the influence of river-basin runoff) with the aim of developing a scientific and operational base for a sustained and rational exploitation and conservation of Southern European Lagoons.

In this context, policies conceived to improve the sustainable use of the natural resources have been analysed considering scenarios in terms of environmental protection and economic development. Scenario identification was facilitated by a preliminary overview of how economic and environmental variables in the study sites interact with each other and affect system behaviour.

After the definition of different scenarios and their prioritization by end-users, a preliminary investigation using qualitative modelling was developed by accommodating economic and environmental variables in a comprehensive model of the Sacca di Goro that describe major interactions between selected compartments. This kind of analysis is specially suited for systems that are partially specified.

In a second step, we addressed the main aspect concerning clam farming activities, using a quantitative approach based on a 3D integrated biogeochemical model. Such approach allowed the assessment of the implications of an increase in the clam farming area.

The focus on clam farming provides only a partial view; however, such scenarios constitute the first iteration in the procedure, and a second iteration is necessary to define the main constraints and boundaries, as well as to incorporate the economic evaluation and social implications of the different options.

Description of the Sacca di Goro lagoon

The Sacca di Goro lagoon is a shallow-water embayment of the Po River Delta (44°47'-44°50' N and 12°15'-12°20' E); the surface area is 26 km^2, the total water volume is approximately 26×10^6 m^3 and the average depth is approximately 1.5 m (figure 1). The lagoon watershed is 860 km^2 and its hydrographic network is for the most part artificially regulated. As a consequence, freshwater flows are partially independent of rain events. In the last decade, the annual freshwater discharge ranged from 336×10^6 (1998) to 594×10^6 (1996) m^{3}y^{-1}. On average, water retention time ranges between 1 and 4 days, although in the sheltered areas water stagnation can occur (Viaroli et al., 2001; Zaldívar *et al*., 2003; Austoni *et al*., 2005; Marinov *et al*., 2005). At present, water exchanges between the Sacca di Goro and the adjacent Adriatic Sea depend on two openings in the southern sand barrier, which are at present approximately equivalent in width (about 900 m). The recent evolution of the Sacca di Goro was characterised by a continuous accretion of the sand barrier, which led to changes in the hydrodynamics. To relieve water stagnation, a channel was cut in 1993 which evolved into a second mouth, whereas the main mouth has narrowed even further. Numerical models demonstrated that in the early 1990s, the eastern area of the lagoon was sheltered and was separated from the western and central zones influenced by freshwater inflow from the Po di Volano and by the sea, respectively. Moreover, the eastern sub-basin was very shallow (maximum depth 1 m) and accounted for one half of the total surface area and for one fourth of the water volume. Here, due to the silting of the main mouth, water stagnation was one of the major causes of the summer dystrophic crises which frequently occurred from 1987 to 1998. Since 1998, the hydrodynamics has been further and radically modified with the dredging of internal canals. During this intervention the dredged material was disposed of in shallow areas in the eastern part of the lagoon to create permanent islands for preventing macroalgal growth and also for supporting clam farming. A synthesis of the main studies carried out in the lagoon in the last twenty years is reported by Viaroli *et al*. (2006). At present, the Sacca di Goro is one of the top European sites for clam rearing. More than one third of the lagoon surface is exploited for clam farming, with an annual production that reached a maximum of approximately 15,000 t y^{-1} in the early 1990s. The corresponding economic revenue has been oscillating between 50 and 100 M€ each year. Currently, clam farming is managed by cooperatives of fishermen that exploit licensed areas, under the control of regional and local authorities. Up to 1,500 fishermen are associated in the cooperatives and are primarily employed in clam farming in the Sacca di Goro and in mussel farming in the adjacent sea. Young clams (5-10 mm in shell length) are continuously collected from natural stocks along the southern sand barrier and then sown in the licensed areas. Due to ample food availability, the commercial size is attained in a few months. Adult clams usually reach a shell length of approximately 4 cm and a total weight of about 10 g. Within the licensed areas clam densities are generally maintained at approximately 500 adult individuals per square meter with peaks of 1000, even if densities up to 2000 individuals m^{-2} are not infrequent. High revenue was and is currently obtained by controlling the product delivered to the market. For this reason, each fisherman and/or fisherman cooperative can harvest a fixed quota that is established day by day, based on the market demand. Harvesting is performed with manual dredging. Detailed information on clam and mussel farming, their economical relevance and environmental impacts are reported by data (Rossi and Paesanti, 1992; Bartoli *et al.*, 2003; Melià *et al.,* 2003; Viaroli *et al.*, 2003; Vincenzi *et al.*, 2005; Nizzoli *et al.*, 2006).

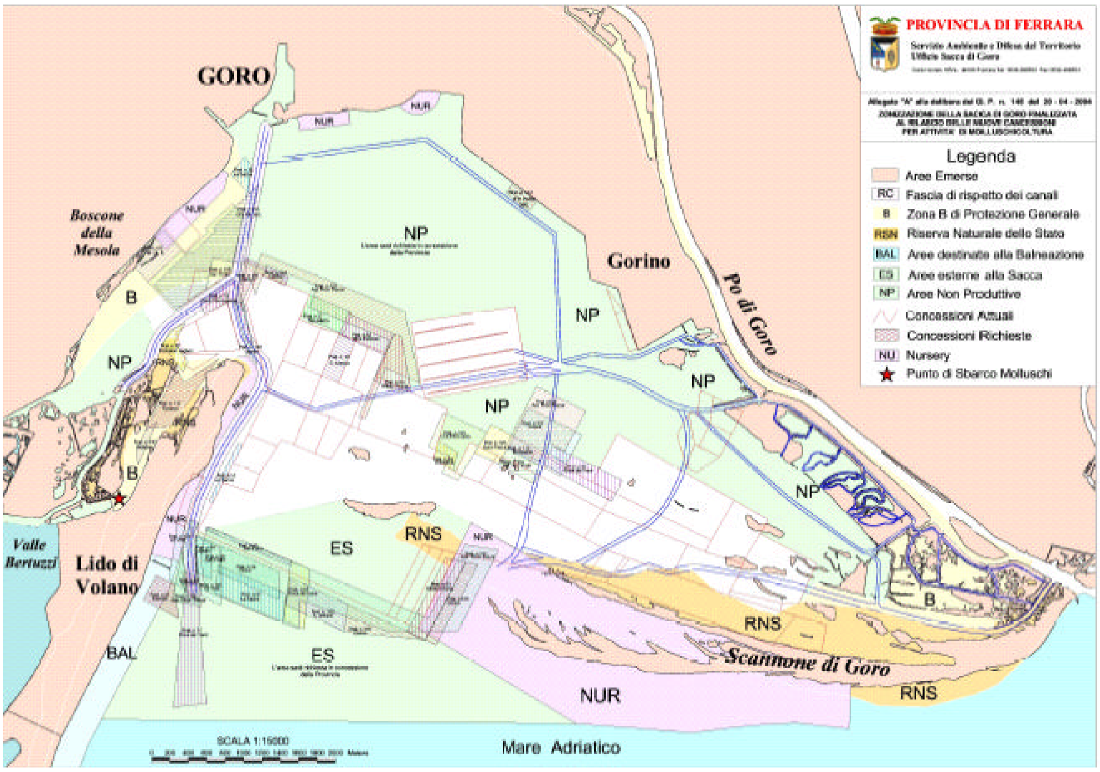

Figure 1. Summary of Sacca di Goro status and future plans for development of shellfish farming activities. Areas which are requested for new farming concession are indicated by dashed zones. Nursery (NU), non productive (NP) and natural reserves (RNS) are also identified.

Main scenarios and options considered in the study

The scenario analysis was designed upon consideration of the main economical activities in the watershed-lagoon system. Information was then organised within a DPSIR scheme. Basically, this approach has allowed the identification of the major drivers, their changes in time and space, and potential indicators for assessing environmental and socio-economic impacts and feedbacks. In term of scenarios one can consider changes in the intensity/quality of driver considered individually or somehow combined. Most of the driving forces should be considered in an integrated view, since when agriculture decreases perhaps tourism and/or industrial activities increase. In this context, four main options were identified and discussed with the decision makers.

Option 1. Development of the farming activity with an increase of the exploited area.

At present clam farming is carried out in an area of approximately 12.6 km^2, in the southern part of the lagoon along the sand barrier. Since 1999, after the new canals were dredged and the water circulation in the lagoon was ameliorated, the fisherman organisations requested an additional area to be exploited.

This zone is approximately 4 km^2 and extends in the eastern part of the lagoon (~2 km^2) and on the marine side of the new formed sand barrier, with an increase of ~2.3 km^2. This request is under evaluation by regional and local authorities. The increase in development of shellfish farming activities is provided by the lagoon management plan of the Ferrara Province (figure 1).

An assessment of the potential risk/impact derived from the enlargement of the farmed area can be made considering the oxygen consumption, nutrient and sulphide fluxes data (Bartoli *et al*., 2003; Melià *et al*., 2003; Viaroli *et al*., 2003; Vincenzi *et al*., 2005, Nizzoli *et al*., 2006) and ecological and hydrodynamics models (Cellina *et al*., 2003; Zaldívar *et al*., 2003a; Marinov *et al*., 2006; Zaldívar *et al*., 2005a).

Option 2. Stabilisation of the farming activity at the actual level with the development of integrated activities either in the lagoon or in the adjacent sea.

At a local scale, there is an attempt to promote a sustainable tourism based on fishery activity, the so called fishery-tourism. In this case, the fishermen are carrying out two activities. The main job is clam farming, whilst the fishery tourism is a complementary activity. The local economy is improved by the direct revenue to fishermen, and indirect revenue to restaurant, hotels and travel agencies. This activity has little or negligible direct impact in the lagoon, whilst potential impacts can be caused along the coast and in the town. This option seems realistic, as this kind of recreational activities are growing in Italy. Moreover, the competition from other lagoons (e.g., Venice and Chioggia, with fewer constraints than in Goro) is causing marketing problems in Goro, where clam prices are higher. Alternative/complementary jobs could therefore supply salary integration.

Option 3. Development of the Regional Park of the Po River Delta.

The eastern part of the watershed and of the lagoon belongs to the Regional Park of the Po River Delta that is going to be transformed into a National Park. It is a Ramsar site for waterfowl protection and a natural heritage under constraints for natural resources and ecosystem exploitation. In the long term, such constrain can potentially cause a conflict with the fisherman companies which are asking for a further development of aquaculture exploitation area. A partial reduction of clam farming in the eastern part of the lagoon could be also foreseen, for example for protecting the red swamp and natural wetlands. Such alternative is contrasted by fishermen who, as the councillors said, consider clam farming as the most important resource for local economy.

Because the natural landscape of the Po Delta has a valuable potential for recreation and tourism, a tourist development can be considered as a way to compensate for income losses due to clam farming restriction, as well as an interesting alternative to this primary activity. Tourism facilities are located along the coast in the same district and basically serve for summer holidays. However, due to the poor water quality and infrastructures, they are less competitive than the southernmost places of the Romagna beaches. Moreover, summer holydays last for less than two months. The conventional tourism could be integrated with fishery-tourism and naturalistic tourism, which potentially covers six months (from April to October).

Option 4. Development of land-based activities.

The watershed of the Sacca di Goro is exploited for agriculture (80% of the total surface, viz 650 km^2). At present there are few main crop typologies (corn and wheat, rice, sugar beets, soybean and vegetable) with are relevant productions often exported outside the area. Corn, wheat, sugar beet and soybean are cultivated with conventional techniques and need pesticides and fertilizers. Therefore, a further development of this activity can be foreseen as a potential impact on water quality and, as a consequence, on lagoon and clam farming. Rice is grown in paddy soils with permanent submersion and needs pesticides and fertilisers. The permanent flooding keeps pesticides and fertilisers in solution and increases the risk of pollution of the lagoon. Vegetables are grown either with conventional techniques or with organic practices, therefore their impact spans from important (green houses) to negligible (organic).

A first rapid assessment of land-based activities can be made with census data (table 1). In turn, impacts which are associated to each activity can be estimated as loadings (tons y^{-1}) that are potentially generated, by converting census data into units of P and N. However, the Po di Volano watershed is strongly influenced by the water derivation from the Po river, which causes a sort of pollution background. Therefore, the control of N and P delivery from the main anthropogenic activities can be biased by the pollution loadings carried by riverine waters. In order to evaluate the relative contribution of those main sources, we used modelling tools developed in the EUROCAT Project (Palmieri *et al*., 2005) using the MONERIS (Modelling Nutrient Emissions into RIver Systems).

Option 5. Climatic changes influence.

Climatic changes may have indirect effects on coastal lagoons, thorough modifications of physical boundaries and system hydrology (Zaldivar *et al*., 2005b). To quantify such changes we used data from the IPCC (Intergovernamental Panel on Climate Change, http://www.ipcc.ch/). In Europe, annual temperatures are expected to warm at a rate of 0.1-0.4°C per decade. Warming is greatest in Southern Europe (Spain, Italy, Greece), with an acceleration of summer trends.

Table 1. Changes in population, livestock and agriculture in Sacca di Goro watershed.

Year		**1991**	**2001**	**Difference**
Human population (Nº inhabitants)		72114	67086	-7,0
Livestock (Nº animals)	*Cattles*	10158	2502	-75,4
	Pigs	8546	14023	+64,1
	Poultry	930588	326451	-64,9
Agriculture main crops (surface, km^2)	*Cereals*	268.7	278.6	+3,7
	Grasses	23.3	27.0	+15.9
	Vegetables	53.5	35.7	-33.3
	Fruit trees	44.8	34.7	-22.5
	Industrial	107.8	122.3	+13.5
	other	45.4	35.4	-22.0

Overall, cold winters are expected to become rarer and hot summers more frequent, although these estimates are subject to high uncertainty. Along with temperature changes, a small decrease of wet depositions is foreseen for Southern Europe, with a maximum of –1% per decade. A marked contrast would occur between winter and summer patterns, with wetter winter and drier summer. In particular, along the Southern European Arc, summer drying is expected to vary of as much as –5% per decade.
The scenarios by the IPCC do not explicitly quantify changes in daily weather extremes. However, it is very likely that frequencies and intensities of summer heat waves will increase throughout Europe; it is also likely that intense precipitation events will increase in frequency, especially in winter, and that summer drought risk will increase in central and southern Europe; and gale frequencies will increase.

Preliminary qualitative modelling analysis
As discussed previously, the core system in the local economy of Sacca di Goro district is clam production. Around this key activity the environment-economy system of the Sacca can be described as in Figure 2. Such representation is mostly conceptual. Based on different scenarios suggested by the end users we tried to accommodate economic and environmental variables in a single model describing major interactions in a qualitative manner (Figure 3).

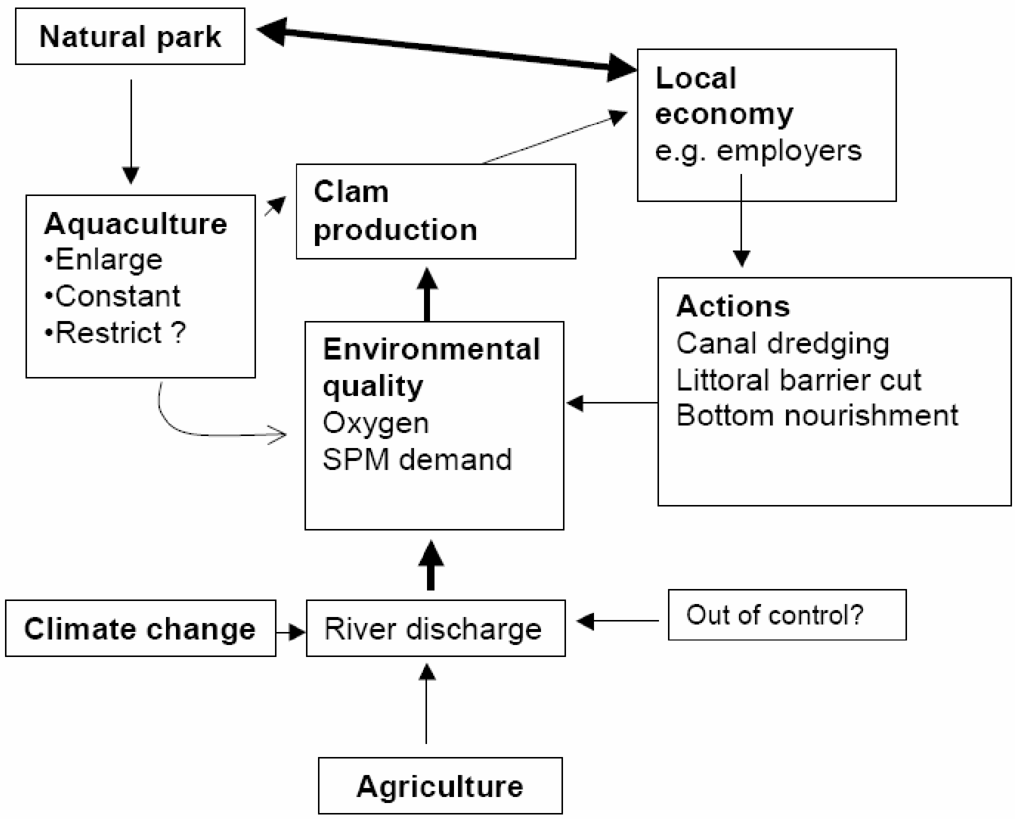

Figure 2. Conceptual representation of the environment-economy system of Goro. River discharge (critical variable is the amount of suspended solid that feeds the lagoon) is included as the main outcome of climate change (SPM: suspended particulate matter).

According to this formalism the model in Figure 3 reads as follows. Clam production benefits local economy.

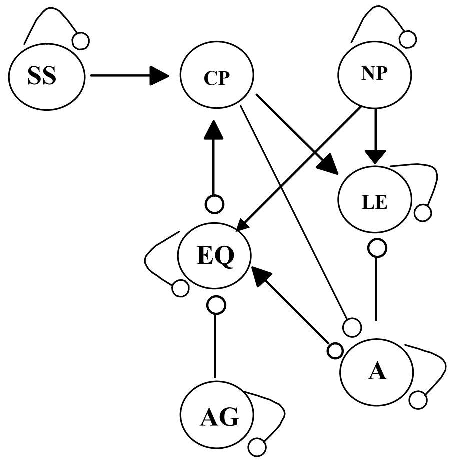

Figure 3. Qualitative model for the environment-economy system of Goro. Symbols: AG= agricultural activity (mainly rice, vegetables and industrial crops); EQ= environmental quality; CP= Clam production; LE=Local economy; A=Action to improve environmental quality, NP= natural park, SS= amount of suspended solid delivered by rivers.

Environmental quality is essential for clam survival, but at the same time clam production may reduce environmental quality because clams produce organic waste that is dispersed in the medium. Resources that are provided by the local economy should be devoted to take actions for improving environmental quality. The higher the production of clams the lower the demand for better environmental quality, as it is now largely acknowledged that life conditions for clams are strictly dependent on the quality of the environment in which they live (i.e. oxygen concentration). That explains the inhibition of clam production on the level of surveillance and action in favour of the environment. Agriculture tends to reduce environmental quality (pesticides and nutrients discharged in the lagoon) and has no benefit onlocal economy: because the domain of investigation is restricted to the municipal area of Goro, where all the economic activities are based on clam production. The role of climate change (or related variables) has been assumed to affect only river discharge and solid transport, which is essential for clam production. All the variables but clam production are self-damped. Self-damping, in general, is intended as a self-regulation process. However, there are other phenomena whose effect yield negative self-effects on variables. Consider the amount of suspended solid (SS) delivered by the Po river. This is a continuous supply of material into the lagoon. That is a constant positive coefficient in the dynamic equation for this variable. The partial derivative with respect to the variable itself (SS) would yield a negative coefficient, which translates into a self-damping on SS in the graph. Any factor which is not considered explicitly in the model but that exerts an important regulative effect on a variable in the model must be taken into account as a self-damping on the variable itself. So, Action (A) may be affected by some bureaucratic inertia, Local Economy (LE) benefits from a continuous supply of resources that come form activities other than calm production, and so forth. Environmental quality does not solely depend on clams and agricultural activity: waste waters from civil discharges come also into the Sacca di Goro and have an effect on water quality. The level of surveillance and action does not respond immediately to reduction of environmental quality, but depends on political decision and there are bureaucratic constraints that act on it. This preliminary scheme must be enriched by including as additional variables the Natural Park (NP), and the quantity of suspended solids (SS) that arrive in the lagoon through river discharge. The former is getting ground as an alternative revenue for local economy improvement and environmental protection; while the latter is a crucial factor for the maintenance of clam productivity as solid material that is transported by the Po River becomes an important source of food for clams.

The qualitative analysis of the model allows drawing some conclusions about the behaviour of the system. Predictions are summarized in table 3 which reads as follows: along a single row one gets the expected variations in the level of the column variable in response to a positive variation in the rate of change of the row variable. Increasing the rate of clam production (last row of the table) improves local economy, reduces environmental quality, and increase clam production. Improving the rate of environmental actions (third row) might have, in the long term, no effect on environmental quality, but it turns to have a positive effect on clam production. Paradoxically, actions conceived to improve environmental quality, such as modifying hydrodynamics or harvesting macro-algae, would not benefit the environment per se, but would have positive repercussions on clam production. Any improvement in the environmental quality due to increased rate of A is taken up by calm production, which is expected to increase. This increase, because clam production negatively affects EQ, would compensate for the beneficial effect on EQ due to the increased level of action, and EQ itself would remain unaffected. The ultimate meaning of such an outcome is that environmental actions are important for the improvement of clam production, although they do not necessarily benefit the local economy (there is a question mark in the table). In fact any improvement in the rate of change of A percolates to the local economy using two active pathways: the direct connection between A and LE, which is a negative link, and the path that connect these two variables through EQ and CP, which carries a positive effect (the signs of the links forming the path must be multiplied to get the overall effect of the path). Whether the positive input on A would benefit LE depends on the relative strength of the two pathways connecting these variables. It is, in fact, a balance of costs and benefits, as actions require economic investments. Stimulating agricultural production has negative effects on local economy and clam production, whereas no consequences are expected on environmental quality. This depends on the fact that the municipality of Goro receives only a limited benefit from agriculture, as its economy is based on clams. Agriculture, however, affects the system because of the pollutants it discharges in the lagoon. Once again, it is the interplay between the systems' feedbacks that determine the outcome. The negative effect of agricultural production on local economy is due to the pathways that connect AG to LE. They are two, both carrying a negative effect. Although agriculture exerts a negative action on EQ, the level of this latter variable remains unchanged when a increase in the rate of change of AG occurs. Because both agriculture and clam production negatively affect environmental quality, what happens is that the negative effect of agriculture is compensated for by the reduced level of clam production. Climate changes may have profound effects clam production, especially when it is considered in the short term. This effect can be proven considering a very dry year, e.g. 2003, when the Po river discharges have decreased noticeably, especially from April to August. In parallel, SS and nutrients discharges have decreased, lowering clam and mussel production, with relevant impacts also on recruitments. If climate change will act in the direction of increasing summer temperature and drought, river contribution in term of solid particles to the Sacca di Goro also will diminish, and likely will stabilize at a lower level than presently characterizes the lagoon. As tables of predictions are calculated by imposing positive variation in the rate of change of variables, the effect of a reduced lower river discharge turns to be a negative input on the rate of change of SS. To obtain the effect of this input it is sufficient that signs of the SS row be reversed, according to the algorithm of loop analysis (Pucia and Levins 1985). As one can see, a reduced inflow of suspended solid material is expected to lower its own concentration in the lagoon, reducing clam production and the level of the local economy. Environmental quality seems to improve as well as the level of surveillance and action. The natural park could, in principle, be beneficial to local economy. Improving park prosperity in fact, is expected to increase the level of local economy, and, also, clam production. NP may benefit local economy both directly and indirectly through its positive action on environmental quality. However to make more explicit this role of the Natural Park it is necessary that the variable itself and its role in the model is explained in detail.

Table 3. Table of predictions for the model of figure 3.

Input node –	**Affected node**						
	LE	**EQ**	**A**	**AG**	**NP**	**SS**	**CP**
LE	+	0	0	0	0	0	0
EQ	+	0	-	0	0	0	+
A	?	0	+	0	0	0	+
AG	-	0	+	+	0	0	-
NP	+	0	-	0	+	0	+
SS	+	-	-	0	0	0	+
CP	+	-	-	0	0	+	+

Quantitative modelling of clam farming scenarios

Scenario quantification

Scenarios for the Sacca di Goro lagoon have been identified considering the options described above, but having as a major criteria priorities indicated by local administrations and end-users associations for the next 10 years. The increase of the clam farming area was selected as the first priority by the end-users and stakeholders. Therefore, specific scenarios were selected considering that in the mid-term, i.e. in the next ten years, the local economy will be developed maintaining business as usual (BAU) practices with a further development of the farming areas.

We selected three scenarios:

- BAU fully corresponds to 2003-2004 status, with all clam farms mainly placed inside the lagoon (Figure 4).
- BAU15 considers a 15% increase in the licensed farm area; the additional areas are placed entirely inside SG (Sacca di Goro) (Figure 5).
- BAU30 considers a 30% increase in the licensed areas, with a 15% inside the lagoon and 15% located along the outer sand barrier (Figure 5).

Clam productivity scenarios were developed based on the previously implemented and validated coupled 3D hydrodynamic-biogeochemical model. The different components of the 3D hydrodynamic-biogeochemical model have been discussed in detail by Marinov *et al*. (2006a) for hydrodynamics, Zaldívar *et al*. (2003a) for ecology and biogeochemistry, and by Zaldívar *et al*. (2003b, 2005) for the stage-based model of clam farming. The coupled model was designed by integrating the biogeochemical models into COHERENS: a 3D hydrodynamic finite-difference multi-purpose model (Luyten *et al*., 1999). The resulting 3D hydrodynamic-biogeochemical model accounts the specific physical and biological processes of the lagoon and address both water column and sediments. The nutrients, phytoplankton, zooplankton, bacteria and *Ulva* dynamics, as well as shellfish farming, are taken into consideration. Due to the frequent anoxic crises in coastal lagoons, special emphasis was dedicated to the simulation of oxygen dynamics. The nutrients fluxes from the watershed and open sea as well as atmospheric inputs, heat flux, light intensity and wind shear stress at the water surface constitute the model forcing functions.

The scenarios for increasing clam farming area (BAU15 and BAU30) were prepared following the input provided by Ferrara Province on the expansion plans already under study. As a first step, only scenarios related to clam farming activities were considered assuming the watershed remains unchanged as well as the climatic conditions corresponded to those of a "normal" year. Models were run considering three major aspects: the presence/absence of *Ulva*, the effect of initial clam density and distribution, clam seeding strategies (density and distributions).

The effect of initial clam density is concerned with the assessment of the model sensitivity to the initial conditions and the variability that one should expect.

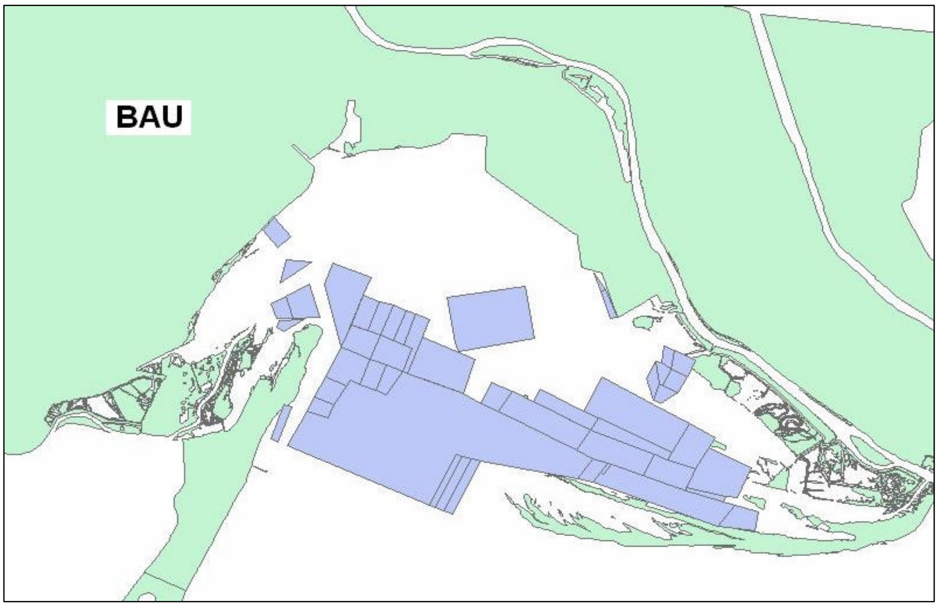

Figure 4. Present status indicating the farming areas (in blue) and the baseline scenario (BAU).

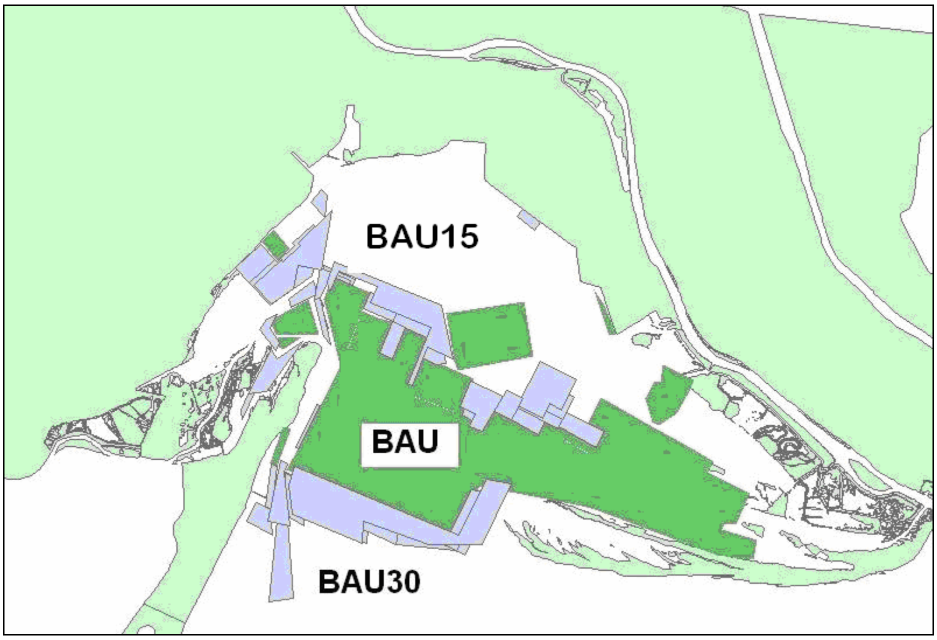

Figure 5. Requested extension of shellfish farming areas by 15% inside the lagoon (BAU15), and by 15% inside plus 15% outside the sand barrier (BAU30).

This effect has been studied under two alternatives, i.e. homogeneous (HO, table 4) and heterogeneous (HE, table 5), taking into account six clam classes based on age/size and their distribution within the lagoon. HO assumed the whole lagoon to have a homogeneous productivity following the simulated results of the 0D model by Zaldívar *et al*. (2003b), whilst

HE uses the initial conditions obtained after one year simulation starting from HO. HE can be assumed to represent the typically occurring distribution, because of the different productivity of different areas in the lagoon.
The seeding density may vary from low -500 individuals per square meter-, normal/typical -1000 individuals per square meter- and high -1500 individuals per square meter- (Castaldelli *et al*., 2003). The presence or absence of *Ulva* in the lagoon has important repercussions in clam productivity and growth (Melià *et al*., 2003; Vincenzi *et al*., 2005; Viaroli *et al*., 2006 and references therein). Furthermore, policies for controlling macroalgal blooms were considered for their socio-economic implications (Cellina *et al*., 2003) as well as for the ecosystem health implications (Zaldívar *et al*., 2005). In this case, the main objective was to quantify in monetary terms the losses in productivity associated with macroalgal blooms.
The three scenarios were developed under the assumptions of no change of both present land use practice and climate. A typical year was defined in terms of meteorological conditions (total yearly precipitation of 593 mm, average annual temperature of 14.8º C, mean annual wind speed of 2.39 m s^{-1}, and average annual humidity of 73.2%). The annual fresh water inputs from watershed and the associated nutrient loads are presented in table 6.

Table 4. Mean initial densities attained by different clam classes at the lagoon scale (HO alternative). Scenario BAU, seeding density 1000 individuals/m².

Clam class	**1**	**2**	**3**	**4**	**5**	**6**
Initial density [ind/m^2]	637	134	193	86	$3.02 \cdot 10^{-2}$	$7.84 \cdot 10^{-7}$

Table 5. Densities attained at different stations in the lagoon by different clam classes under natural conditions (HE alternative). Scenario BAU, after HO, seeding density 1000 individuals /m².

Stations	**Clam class - initial density [ind/m^2]**					
	1	**2**	**3**	**4**	**5**	**6**
Central zone (st. 11)	617	120	61	16	$5.67 \cdot 10^{-3}$	$1.47 \cdot 10^{-7}$
Central zone (st. 22)	624	123	118	47	$1.63 \cdot 10^{-2}$	$4.24 \cdot 10^{-7}$
Western zone (st. G)	620	122	64	17	$6.01 \cdot 10^{-2}$	$1.56 \cdot 10^{-7}$
Eastern zone (st. 8)	625	135	133	55	$1.94 \cdot 10^{-2}$	$5.02 \cdot 10^{-7}$

Table 6. Freshwater and nutrient loadings delivered from watershed to the Sacca di Goro lagoon used for the simulation of the three BAU scenarios.

	Discharge [m3/year]	**Ammonium [tons/year]**	**Nitrate+Nitrite [tons/year]**	**Total P [tons/year]**
Po di Volano	$207.0 \cdot 10^6$	228	1288.0	33.2
Giralda	$23.7 \cdot 10^6$	9.30	189.8	2.80
Bonello	$6.90 \cdot 10^6$	4.60	128.6	1.10
Bianco	$33.4 \cdot 10^6$	29.40	570.1	5.60
Po di Goro	$206.0 \cdot 10^6$	25.8	1737.0	32.5

Scenario simulation without Ulva

The three scenarios BAU, BAU15 and BAU30 were simulated considering macroalgal growth as negligible, as it has actually been occurring since 1998, when the last extended *Ulva* bloom was observed. Later, canal dredging and reshaping of the bottom limited both macroalgal growth and spreading, although in the last two years further modification in the lagoon hydro-geomorphology have caused *Ulva* growth to reduce further. A typical seeding density of 1000 individuals per square meter was assumed. Initial clam densities and class distribution were those of HO conditions.

The model outputs indicate that total production correlates to the area exploited for clam farming, with a significant increase from BAU to BAU30 (table 7). The increase of licensed areas from BAU to BAU15 is ca 2.0 km^2 with a production increase of 3470 tons of clams. In BAU30, licensed areas are 2.2 km^2 greater than in BAU15, with a net production increase of about 4600 tons of clam. This is due to the fact that in BAU15, the expansion of concessions occurs inside the lagoon, where the main productive areas are already occupied. On the contrary, in BAU30 high productive zones can be potentially explored, even if the most appreciated fields are still exploited. The spatial representation of model results is given in figures 6-8. This result is in agreement with other findings which demonstrated that only the marine-influenced areas of the lagoons have a degree of suitability for clam farming (Vincenzi *et al.*, 2005).

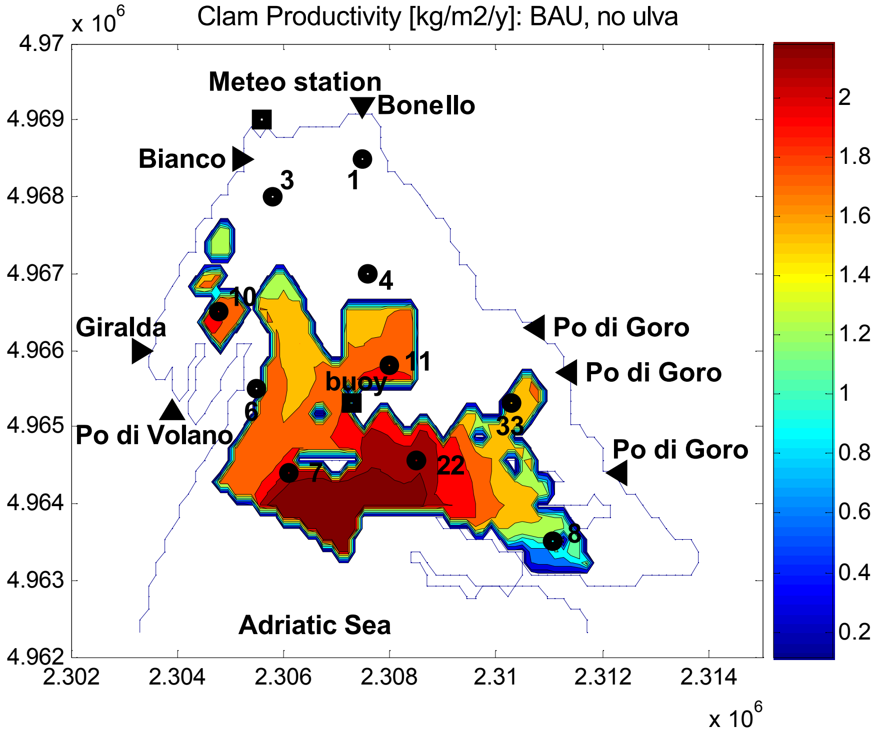

Figure 6. Annual clam productivity in Sacca di Goro for BAU.

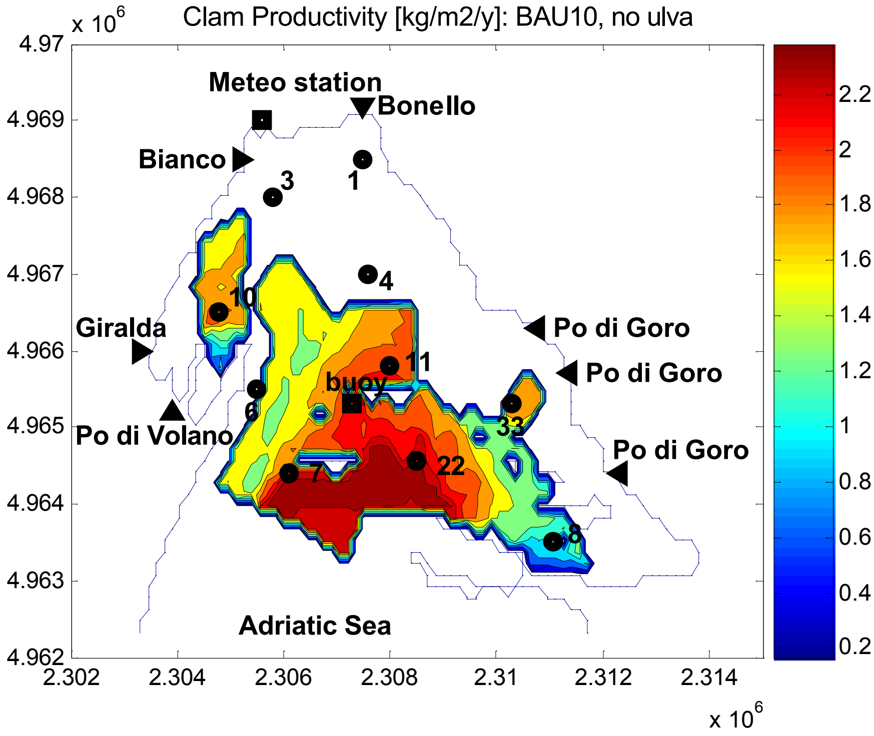

Figure 7. Annual clam productivity in Sacca di Goro for BAU15.

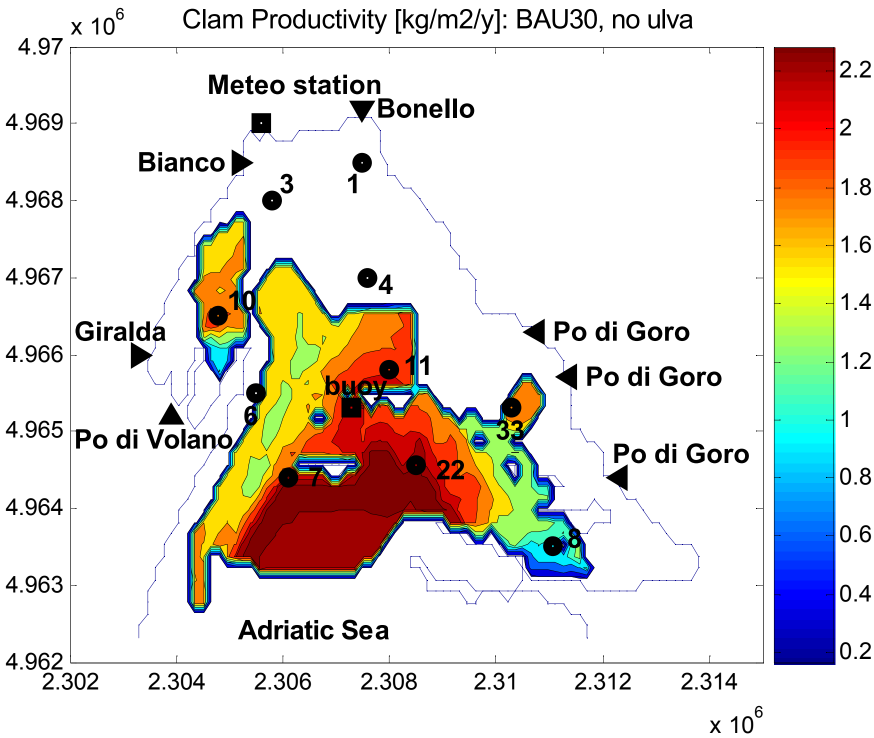

Figure 8. Annual clam productivity in Sacca di Goro for BAU30.

Table 7. Results in terms of total, maximum and average production for the three considered scenarios.

	Aquaculture area [km^2]	Total clam production [tons]	Clam productivity [kg m^{-2} y^{-1}]		Average clam productivity [kg m^{-2} y^{-1}]
			max	min	
BAU-No *Ulva*	12.6	22769	2.28	0.44	1.81
BAU15-No *Ulva*	14.6	26239	2.41	0.44	1.80
BAU30-No *Ulva*	16.9	30855	2.34	0.44	1.83

Table 8. Results in terms of total, maximum and average production for the two considered scenarios without *Ulva*.

	Initial density [ind m^{-2}]	Total clam production [tons]	Clam productivity [kg m^{-2} y^{-1}]		Average clam productivity [kg m^{-2} y^{-1}]
			Max	Min	
BAU-no *Ulva*	HO	22769	2.28	0.44	1.81
	HE	21578	2.50	0.28	1.71
BAU30-no *Ulva*	HO	30855	2.34	0.44	1.83
	HE	27577	2.45	0.29	1.63

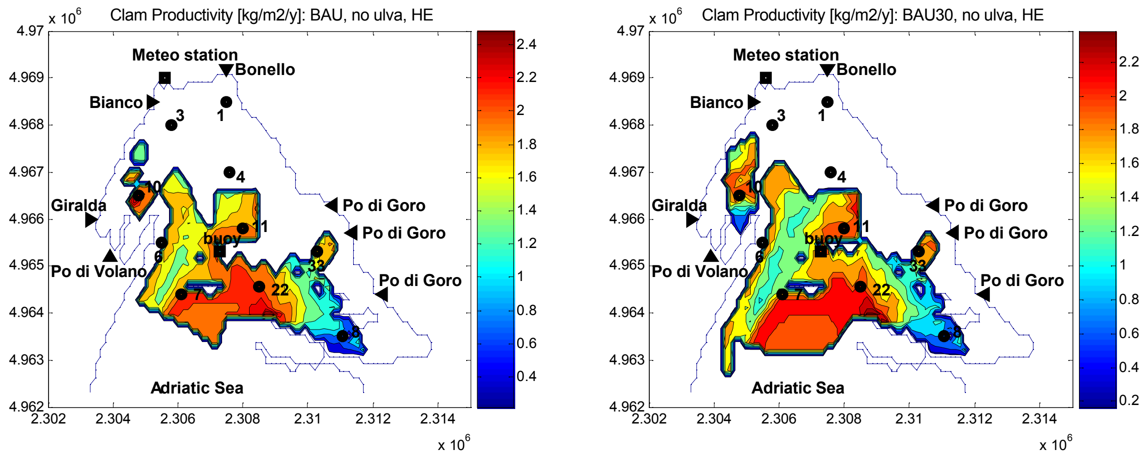

Figure 9. Annual clam productivity in Sacca di Goro for: a/ BAU-no *Ulva* and heterogeneous (HE) clam density as initial conditions; b/ BAU30-no *Ulva* and heterogeneous (HE) clam density as initial conditions.

Seeding strategies in the scenario simulation without Ulva

In the Sacca di Goro lagoon, clam production is only partially sustained by the natural stock recruitment, whilst for the most part farming activities are supported by seeding juvenile stages collected along the sea-side of the sand-barrier. The production of clam seeds is controlled by few cooperatives, therefore the seeding effort can represent a relevant cost in the farming management. Seeding density is important as well, since the total production depends on the initial clam density.

The simulations discussed above were run at an intermediate density of 1000 individuals per square meter, which can be considered as a realistic estimate of the current practices. Likely, in the most productive areas lower seeding densities can give similar yields, whilst in the less suitable zones, a greater seeding effort might lead to an unsuccessful exploitation.

The causal effect of seeding densities upon annual production was tested only for the BAU scenario (current exploitation) considering both HO and HE alternatives. In this context we considered seeding densities of 500, 1000 and 1500 individuals per square meter. The results obtained are summarized in Table 9 and Figure 10. For the case of HO conditions, a 50% decrease of average seeding density resulted in about 7.75% reduction in total clam production, whereas a 50% increase rose harvesting up to 9.86%. For the case of HE conditions, the lower seeding density (500 individuals per square meter) caused a production loss of 10.78%, whereas the higher seeding density (1500 individuals per square meter) increased the total production of 8.63%. On average, a 50% change of seeding density leads to a variation change from ~8% to ~10% variation of total clam production. These results have been obtained considering that there is no *Ulva* in the lagoon. Furthermore, no attempt has been made to optimize the seeding periods, considered constant following Zaldívar *et al.*(2003b).

Scenario simulation with Ulva

Ulva has a negative impact on clam production (Viaroli *et al.*, 2006) since its decomposition produces a considerable amount of organic matter, increasing the microbial loop activity with the subsequent oxygen depletion. Therefore, to assess the impacts of *Ulva* several scenarios should be studied at several *Ulva* biomass concentrations.

Table 9. Results in terms of total, maximum and average production for the three considered seeding scenarios (500, 1000 and 1500 ind./m^2).

	Seeding density [ind m^{-2}]	Total clam production [tons]	Clam productivity [kg m^{-2} y^{-1}]		Average clam productivity [kg m^{-2} y^{-1}]
			Max	Min	
BAU-no *Ulva*,HO	500	21004	2.05	0.44	1.67
	1000	22769	2.28	0.44	1.81
	1500	25013	2.68	0.40	1.99
BAU-no *Ulva*,HE	500	19252	2.15	0.44	1.53
	1000	21578	2.50	0.28	1.71
	1500	23440	2.77	0.27	1.86

To address this aspect we have studied only for BAU case two specific scenarios - the first one considers a severe *Ulva* bloom, whereas in the second scenario, *Ulva* growth was simulated at a considerably lower biomass level. The results have been obtained using two different sets of meteorological forcing (winds and tides), whereas the rest of the model forcing, i.e. water and nutrient loadings have remained unaltered. The model suggests that probably the meteorological conditions in the first three months of the year have a considerable impact on the future dynamics of *Ulva*. The differences in the temporal development of *Ulva* biomass under blooming and low biomass circumstances are reported for five stations in the lagoon. Under bloom conditions, a biomass peak up to 300 g m^{-2} was attained in the easternmost sheltered area, where water stagnation frequently occurred (Figure 11). Furthermore, macroalgal beds spread over the Southern-central part of the lagoon, attaining up to 100 g m^{-2}. The macroalgal development with lower biomass levels, impacted only the easternmost zone of the lagoon, where the simulated biomass never exceeded 200 g m^{-2} (Figure 12). The simulated growth cycles of *Ulva* conformed to patterns observed in the decade 1989-1998, when huge blooms covering more than 50% of the lagoon surface alternated with slow growth of patchy stands (Viaroli *et al*., 2006). Overall, growth patterns and the spatial distribution of *Ulva* seemed to be affected more by physical factors, rather than by nutrient availability, although in shallow marine areas nutrient have been considered as the starter of mass blooms of nuisance seaweeds (Dahlgreen and Kautsky, 2004). Further research is necessary to clarify this point, but probably an early warning system based on meteorological data could be developed to estimate the probable amount of Ulva expected for spring and to decide whether or not removal of *Ulva* would be necessary. The effects of different *Ulva* biomass on clam production were assessed for the BAU scenario assuming a normal seeding effort (1000 individuals per square meter). Initial clam density and distribution were as in the simulation runs without *Ulva*. In Figure 13 the total annual harvest of clams under no *Ulva*, low *Ulva* and *Ulva* bloom scenarios are compared in detail during one simulation year. Compared to the no *Ulva* situation, the reduction of annual clam production was about 28.3% under *Ulva* bloom and 14.3% for low *Ulva* growth occurrence. The influence on clam productivity of *Ulva* growth and spreading within the lagoon is also shown in Figure 14.

Here, one can observe the restriction of the zone suitable for clam production which occurred mainly in the inner lagoon side, where the risk of anoxia was greatly increased by the massive macroalgal growth. Finally, the unfavourable impact of *Ulva* bloom (maximum growth) on clam farming was studied for the present (BAU) and expected scenarios (BAU15 and BAU30) of the enlarged farm areas (Fig. 15). Seeding density (1000 individuals per square meter), initial clam density and distribution were as in the simulation runs without *Ulva*. Details in terms of total, maximum and average production for all considered scenarios and comparison with cases of no *Ulva* are given in Table 13. In addition, maps of the annual clam productivity for BAU 15 and BAU30 are presented in Figure 15. Considering the presently exploited area (BAU) without algal growth as a reference, there is at least 14.3% reduction in the total clam production due to the presence of *Ulva* inside the lagoon. This corresponds approximately to 13 M€ assuming a market price of 4 € per kg of clams.

For BAU15 the reduction is higher, i.e. 16.7%, which corresponds to approximately 17.5 M€, whereas for BAU30 the percentage of reduction is quite similar to BAU, i.e. 13.6%, which in this case counts approximately to 16.8 M€ of losses. For the last case it is obvious that the area outside the lagoon is less affected by the presence of *Ulva*, which usually grows inside the lagoon.

Furthermore, the Ulva scenarios evidence that an increase of farmed area inside the lagoon makes the total clam production highly vulnerable to macroalgal blooms. In the scenario with *Ulva*, most of the crop losses occurred in the inner part of the lagoon.

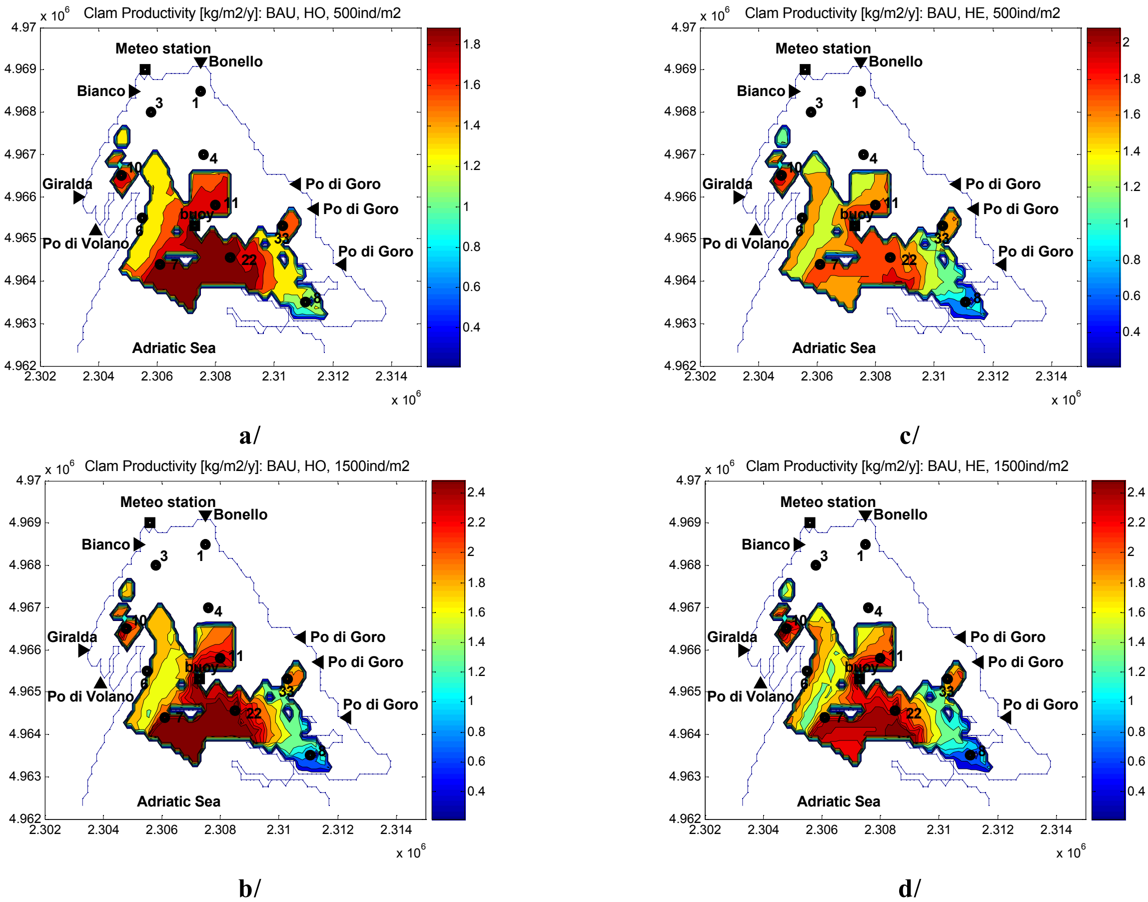

Figure 10. Annual clam productivity in Sacca di Goro for : a/ BAU-no *Ulva*, homogeneous (HO) clam density and low seeding as initial conditions; b/ BAU-no *Ulva*, homogeneous (HO) clam density and high seeding as initial conditions; c/BAU-no *Ulva*, heterogeneous (HE) clam density and low seeding as initial conditions; d/ BAU-no *Ulva*, heterogeneous (HE) clam density and high seeding as initial conditions

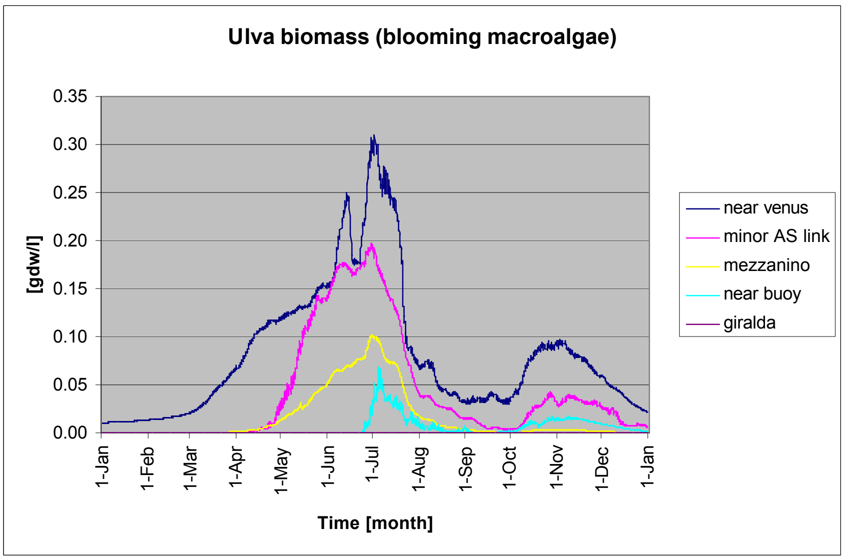

Figure 11. Temporal development of *Ulva* biomass during a simulation of a bloom formation in five stations in the Sacca di Goro lagoon.

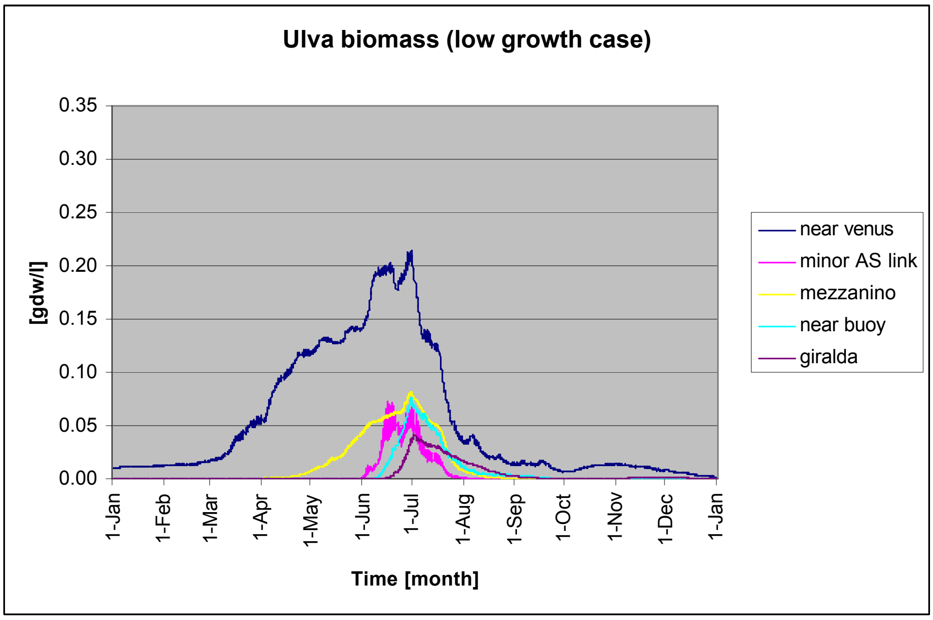

Figure 12. Temporal development of *Ulva* biomass during a low-growth simulation in five stations in the Sacca di Goro lagoon.

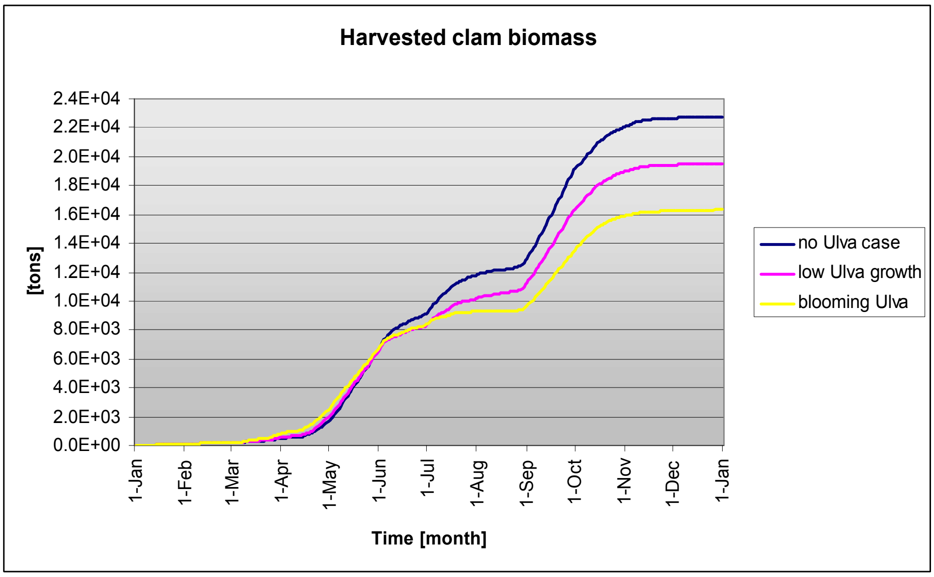

Figure 13. Annual clam harvest for *no Ulva, low Ulva* and *Ulva bloom* scenarios.

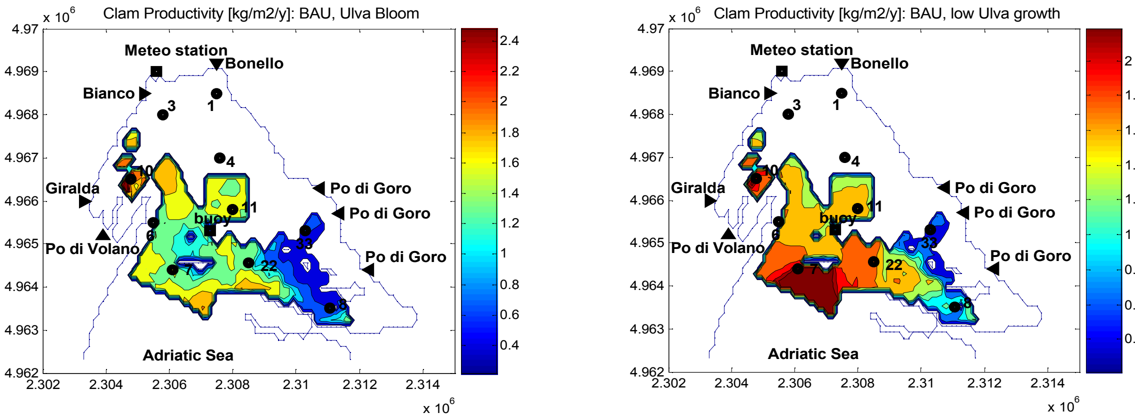

Figure 14. Annual clam productivity in Sacca di Goro for: BAU in case of high *Ulva* bloom (left); low *Ulva* growth (right).

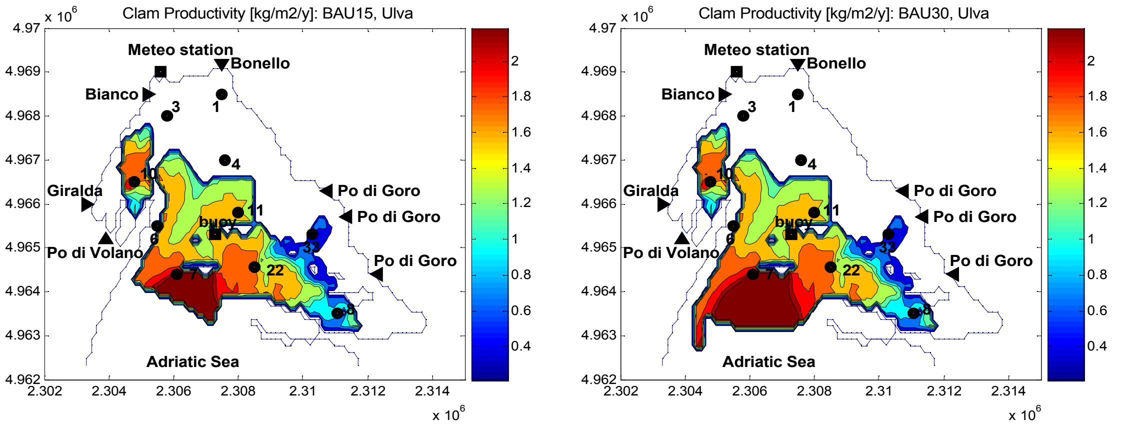

Figure 15. Annual clam productivity in Sacca di Goro for: BAU15 with *Ulva* bloom (left); b/BAU30 with *Ulva* bloom (right).

Table 13. Total, maximum and average production for the three considered scenarios with and without *Ulva* growth

	Aquaculture area [km^2]	Total clam production [tons]	Clam productivity [kg m^{-2} y^{-1}]		Average clam productivity [kg m^{-2} y^{-1}]
			max	min	
BAU -	12.600	22769	2.28	0.44	1.81
BAU- *Ulva*	12.600	19523	2.29	0.31	1.55
BAU15	14.603	26239	2.41	0.44	1.80
BAU15- *Ulva*	14.603	21849	2.29	0.31	1.49
BAU30	16.875	30855	2.34	0.44	1.83
BAU30- *Ulva*	16.875	26651	2.29	0.31	1.58

This was probably due to the increased oxygen demand of oxygen which was caused by biomass decomposition. Moreover, in the central and sheltered zones of the lagoon, the system reached the maximum carrying capacity and therefore perturbations were expected to have a stronger effect.
The dynamics of oxygen with and without *Ulva* is illustrated in Figure 16. Without *Ulva*, oxygen followed more closely the typical annual behaviour as a function of temperature, i.e. higher values at low temperature. The occurrence of *Ulva* blooms led to a considerable oxygen increase in spring, which corresponded to the active growth of macroalgae. Afterwards, anoxic conditions established as a consequence of the decomposition of the accumulated biomass (see also Viaroli *et al.*, 2001). The anoxic conditions were assumed to be responsible of an increase in the mortality of clams and therefore the main cause of a reduction in their production.

Future scenario analysis

Following the preferences indicated by end-users and stakeholders in the Sacca di Goro lagoon, we have focused this first scenario analysis on the study of clam productivity and its sensitivity to several initial conditions and boundary effects.
A further implementation of the quantitative approach to lagoon scenarios will consider changes in the human activities occurring in the watershed. In the context of the WFD, policy oriented practices will be strengthened in order to achieve the good ecological status of inland and coastal waters. Likely, this goal can be attained by changing agricultural policies in terms of reduction of fertilisation rates and modification of agronomic rotation schemes. Further reduction of the pollution loadings will be achieved through improvements of the performances of wastewater works. To discriminate between local sources and background loading delivered from the Po River, scenarios from EUROCAT project (http://www.iia-cnr.unical.it/EUROCAT/project.htm) concerning the Po River will be used to define water quality entering into the Sacca di Goro watershed.

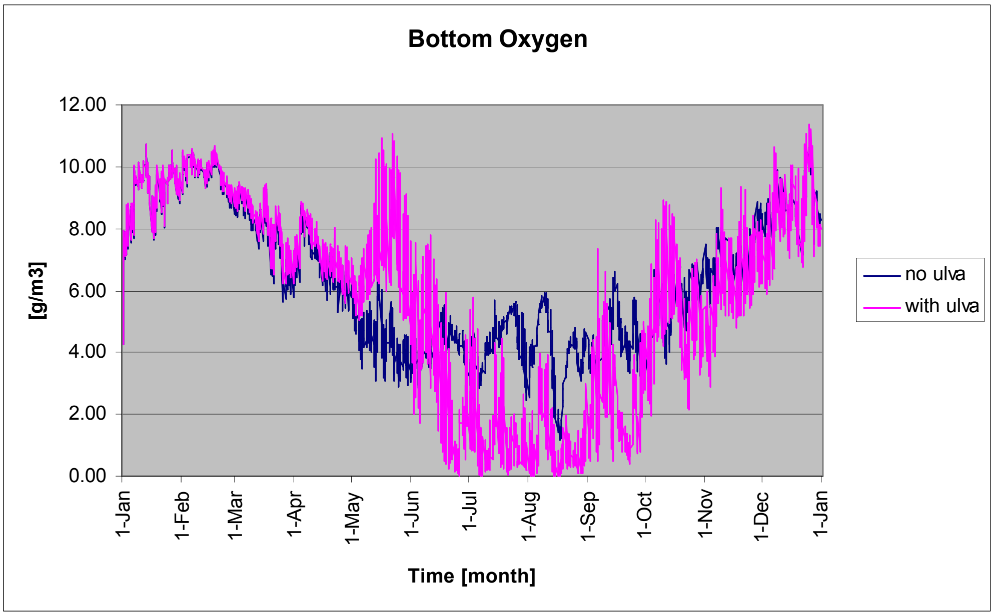

Figure 16. Example of oxygen concentrations in the bottom water layer for BAU with and without *Ulva*.

Finally the climatic influence will be considered by simulating a full range of hydrological conditions spanning normal, wet and dry years. However as the Sacca di Goro watershed is a heavily human regulated system, water flows will not change considerably.

More important effects are expected from nutrient reduction scenarios that should consider the importance of the Po River as well as that of the Adriatic Sea (and indirectly the Po River).

Conclusions

There is a need for an integrated approach for the management of coastal systems and integrated models are useful tools to analyze the complex relationships between anthropogenic pressures and natural variability.

Concerning the analysis of scenarios devoted to clam farming productivity, and as general conclusions, it seems that increasing the area inside the lagoon would decrease slightly the average productivity but would certainly increase the risk of anoxic conditions and the vulnerability of the clam production against macroalgal blooms by increasing its economic impact. On the contrary, the increase of area devoted to clam farming outside the lagoon would increase the average productivity maintaining the risk of anoxic conditions and the vulnerability to macroalgal blooms at similar levels.

Also evident from the results is the fact that Ulva growth and water circulation have an important effect on total clam production. This effect would be exacerbated with an increase of clam farming area inside the lagoon, becoming in this case essential the fast removal of Ulva to avoid macroalgal blooms.

However, in order to have a complete picture of the dynamics in Sacca di Goro, it is necessary to analyse the effects of changes in nutrients from the Burana-Po di Volano as well as from the Adriatic and to consider the effects on clam production of dry and wet years to include climatic effects in the simulation runs.

Acknowledgements.

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