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Manila clam introduction in the Sacca di Goro Lagoon (Northern Italy): ecological implications

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Abstract: The manila clam was introduced in 1986 in the Sacca di Goro lagoon (Po River Delta, northern Italy) and in a few years became one of the backbone of the local economy. Few years later, the lagoon was affected by macroalgal blooms, followed by the biomass breakdown which impacted the clam farming, with mass mortality in summer. From late 1987 to 1994, an intensive, monthly-based monitoring plan of water column was thus performed, aiming at analyzing salinity, dissolved oxygen, chlorophyll a and nutrient patterns in a grid of sampling stations, with respect to hydrodynamics and freshwater inputs. Later on, monitoring of spatial distribution, biomass evolution and ecophysiology of the dominant macroalgal community was performed (1990-1998), together with experiments focusing on macroalgal production and factors controlling macroalgal growth and decay. Furthermore, the role of clams in coupling benthic and pelagic processes was addressed as a possible feedback loop in the lagoonal ecosystem. Regular monitoring was afterwards flanked by an experimental approach aiming at more detailed studies of how clams affect benthic processes, in particular aerobic and anaerobic respiration, nutrient recycling, the regulation of denitrification and the analysis of nitrogen cycling within farmed areas (1993-2005). More recently, different European projects addressed the relationships between environmental and socio-economic issues in the clam farming management. In this review we summarize the main outcomes of these research activities with the overall aim of quantifying, at the lagoon scale, the role of the farmed species as regulators of some of the multiple processes involved in the ecosystem metabolism and biogeochemistry. Special emphasis is given to how clams affect uptake, dissipation and recycling pathways of nutrients, especially nitrogen. Overall, the clam farming system is analyzed for its implications in the whole lagoon metabolism and for possible ecological feedbacks which in turn can impact the local socio-economic system.

Key words: Sacca di Goro, Asari clam, sediments, fluxes, anoxia, macroalgae

Estuarine eutrophication: effects, external and internal causes

Eutrophication of coastal areas has generated a huge research effort worldwide since the late 70's. Nutrient delivery to brackish and shallow marine areas, in particular nitrogen loadings, have stimulated primary production and the input of organic matter to the benthic system, with cascading effects for the biota and the matter cycling (Nixon, 1995). Among recognized and well documented negative effects of eutrophication are the shift of primary producer communities (from macrophytes or microphytobenthos to phytoplankton or macroalgal dominated), increased sediment resuspension, erosion and water turbidity, higher demand of electron acceptors by the benthic compartment, sediment and water anoxia and dystrophy (Cloern, 2001). The mechanisms leading to the latter, extreme event were studied and clarified in detail

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(Viaroli *et al.*, 2008; 2010; Zaldivar *et al.*, 2009). Under eutrophic conditions, labile organic input to sediments exceeds the mineralization capacity of the benthic compartment and decouples reduction and oxidation processes, leading to the accumulation of the end products of anaerobic microbial metabolism. The progressive decrease of dissolved oxygen in the bottom water and sediments, the exhaustion of oxidized Fe and Mn pool and the migration of free sulfides to the interface then occurs (Giordani *et al.*, 1996; Zilius *et al.*, 2015). Sulfides are extremely toxic and may kill phanerogams and macrofauna, hampering their metabolic role, including sediment reworking and oxidation, enhancement of P retention and of N loss via coupled nitrification and denitrification, nutrient uptake at the interface and oxygen production in the proximity of sediments (Nizzoli *et al.*, 2007; Bartoli *et al.*, 2008, 2012). Sulfides may also inhibit the activity of denitrifying bacteria and produce a short circuit within the geochemical P buffer mechanism, resulting in large releases of inorganic N and P from sediments, with a positive feedback for eutrophication phenomena (Bartoli *et al.*, 1996; Giordani *et al.*, 1996; Viaroli *et al.*, 2010; Zilius *et al.*, 2015).

However, eutrophication may also have positive aspects for coastal areas. Early eutrophication phases (the so-called *enrichment stage*) for example result in increased fish biomass, as the energy flow within ecosystems increases and supports higher trophic levels. The growth of mollusks may also be favored by moderate eutrophication due to increased phytoplankton availability (Naylor *et al.* 2000; Newell, 2004).

Nutrient enrichment and mollusks farming in the northern Adriatic lagoons (Italy)

The lagoons of the Po River Delta and of the Northern Adriatic coast of Italy receive heavy loads of nutrients generated in the Po Plain, an area which is heavily exploited for agricultural and industrial activities (Viaroli *et al.*, 2013; 2015). A number of watersheds within the Po River basin are characterized by unbalanced nitrogen (N) budgets, with input terms from manure, synthetic fertilizers and, to a lesser extent, urban wastewaters largely exceeding outputs (N uptake by crops), *sensu* Oenema *et al.* (2003). As a consequence, the risk of diffuse water pollution by the N excess is extremely elevated (Bartoli *et al.*, 2012; Castaldelli *et al.*, 2013). Nitrogen loads generated in the agricultural sectors of the Po basin and transported towards the Adriatic Sea generally exceed the metabolic capacity of the transitional zones, resulting in eutrophic to hypertrophic conditions of brackish areas (Abbiati *et al.*, 2010).

The retrospective analysis of the last three decades of the Sacca di Goro Lagoon allows to review the eutrophication phenomena in a deltaic area receiving nutrient-rich freshwater from a basin under multiple human pressures. In this small lagoon, nutrient enrichment and its effects on organic matter production and final fate (eutrophication) must be considered in a comprehensive manner, together with the analysis of other co-occurring socio-economical and environmental changes. Macroalgal blooms and collapses overlapped drastic changes in the local economy, consequences of the successful introduction in the lagoon of the clam *Ruditapes philippinarum*. This farming activity proved to be one of the most commercially successful introduction of an exotic species in a lagoon environment. Clams farming was linked to the lagoon eutrophication with both positive (fast mollusks growth, high yield) and negative (anoxia and massive death of mollusks) feedbacks. Furthermore, human interventions to protect the commercial activity from dystrophic events (i.e. intervention on sand bars and canals to improve water circulation within the lagoon) had other important consequences on water quality.

The effect of clams farming on the lagoonal environment can be synergic and similar to that of eutrophication as sediment dredging to recover clams destroys meadows of rooted phanerogams, enhances the regeneration of nutrients and sediment resuspension, augments locally the chemical consumption of oxygen and, via the deposition of feces and pseudo feces, results in organic matter input to surface sediments that further enhances sediment oxygen demand and nutrients recycling (Bartoli *et al.*, 2001; Castaldelli *et al.* 2003; Viaroli *et al.* 2003). Molluscs farming can also favor changes in the primary producer community as mollusks promote water transparency with their filtration activities, removing phytoplankton, and excrete inorganic nutrients readily available to opportunistic and not ingestible macroalgae. Simultaneously, mollusks farming can be antagonist to eutrophication as filter feeders remove large fractions of the particulate matter in the water column and convert nutrients in biomass which is exported from the sites of farming (Viaroli *et al.*, 2010).

In this review we analyse the recent evolution of the Sacca di Goro, linking external nutrient-associated eutrophication with internal changes in the lagoon, after the establishment of mollusks farming, the most relevant economic activity. Special emphasis is given to nitrogen cycling, and in particular to the analysis of assimilative and dissimilative pathways and their regulation by environmental factors.

The Sacca di Goro Lagoon

The Sacca di Goro (44.78–44.83°N and 12.25–12.33 °E) is a small (26 km^2) and shallow (mean depth ~1.5 m) eutrophic lagoon located in the Southern part of the Po River Delta, in the Province of Ferrara (Fig. 1). The lagoon watershed extends over 860 km^2 and is partially subsident and man-regulated. The lagoon receives freshwater inputs from the Po di Volano and a series of scooping plants which drain the lagoon surroundings. The salinity is dynamically variable as a function of the balance between freshwater and tide-driven marine inflows. The western and eastern corners are influenced by freshwater inputs while the central area is more marine. Additional freshwater inputs are from the Po river through the Po di Goro branch and the river plume which enters into the lagoon from the Adriatic Sea. Sediments are a mosaic of sandy, silty and clayey zones; depending upon currents. Sandy areas are located close to sea mouths, whilst muddy areas are common in the more stagnant eastern corner and central area. In the last decade, dredging activities have increased dramatically, aiming at the replacement of muddy with sandy areas, to expand the lagoon surface suitable for clams farming.

The lagoon is eutrophic and from mid 1980s blooms of green macroalgae from the *Ulva* complex have determined anoxic crises and dystrophic outbreaks in summer. Early ecological studies in this lagoon were started by the Universities of Ferrara and Parma in the late 1980's and were stimulated by the Ferrara Province administration as macroalgal blooms were impacting clams farming, a fast developing economical activity. More details and references on the lagoon hydrology, ecology and pollution are reported by Viaroli *et al.* (2006; 2010).

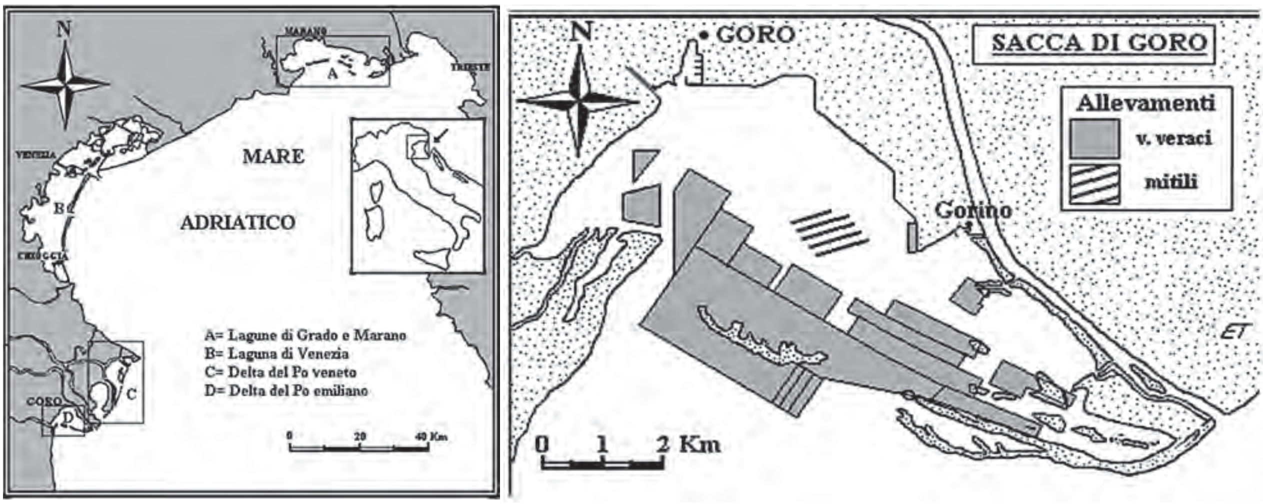

Fig. 1. The north Adriatic coastal lagoons (A=Grado and Marano, B=Venice; C=Po Delta, Veneto Region; D=Sacca di Goro, Emilia Romagna Region) where Tapes philippinarum is farmed. The detailed map of the Sacca di Goro shows areas licensed for clams seeding, in grey.

Ruditapes philippinarum in the Sacca di Goro

The Asari clam was introduced in Italy nearly three decades ago and its farming became rapidly one of the most important economic activity within national aquaculture products. Main sites of production were the lagoons of the Northern Adriatic Sea (Marano-Grado, Venice and those within the Po River Delta, Fig. 1). The production peaked exponentially, reaching in 1999 some 65,000 t yr^{-1}; at present the national production is nearly 35,000 t yr^{-1} (2013) which represents approximately the 70% of the European clam production (Fig. 2). The main reason for such decrease is the much lower contribution of the Venice lagoon to the total, as a consequence of multiple factors (oligotrophication of the lagoon, anoxia, parasites, bad management of the resource). Elsewhere (Goro Lagoon, the study case presented) the production remained stable or even tended to increase due to appropriate management practices, targeting the substrate, water circulation through the tidal canals, the control of macroalgae and the realization of a nursery area in the open sea.

In the Sacca di Goro lagoon clam farming was started in 1986, becoming the main economic activity only five years later. Actually, more than half of the lagoon surface (15 km^2) is exploited (Fig. 1), with an annual production between 15,000 and 18,000 t yr^{-1} (Fig. 2). Local fishermen cooperatives manage the sowing and the harvesting of the clams in well-defined licensed areas. At the beginning of the farming activity, licensed areas were mainly located in the southern area of the lagoon (Fig. 1) where the water exchange rate is higher and the sediments are sandy. Now clams are also sown in muddy substrates, in areas with strong freshwater influence. Young clams (0.5–1.0 cm in shell length) are continuously collected within or in the sand banks just outside the lagoon and immediately sown until they reach the commercial size (2.5–4 cm); in the Sacca di Goro, due to high food availability, this occurs in 8–10 months. More recently, nursery areas outside the lagoon were established in order to provide young clams to fishermen in case of massive death within the lagoon. It is also a common practice to move large amounts of clams from the lagoon to the sea (and vice versa) to avoid loss of product in very dry and hot summers when the risk of

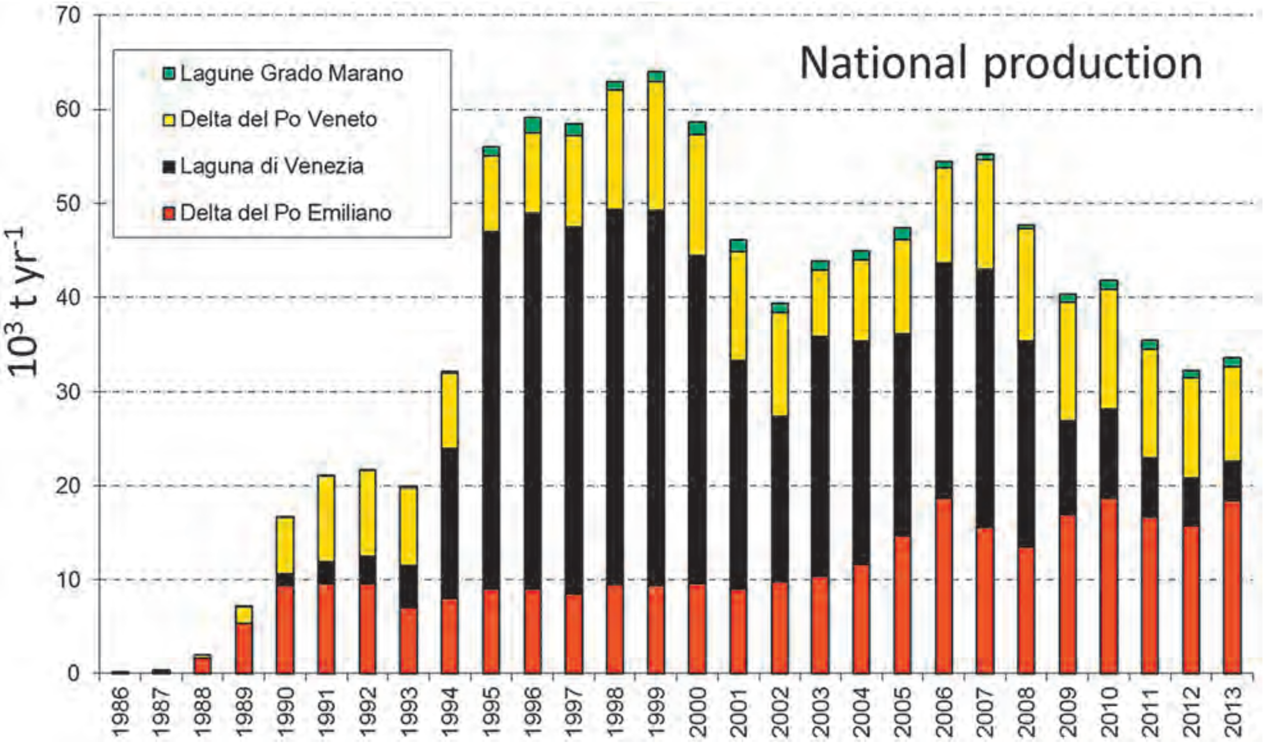

Fig. 2. Temporal evolution of the Asari clam production in Italy. The red bar represents the production within the lagoons of the Emilia Romagna Region, almost entirely represented by the Sacca di Goro.

anoxia is elevated. *Ruditapes* densities are generally maintained at around 1000 adult individuals m^{-2}; but densities may be higher in well flushed areas, with some risks due to their elevated metabolic activity.

Despite its small dimensions, the Sacca di Goro lagoon supports the local economy and provides the main revenue of the resident population, which ranges between 50 and 100 million euros yr^{-1}. Shellfish farming is socially relevant, it ensuring about 1,500 direct job positions, plus employments in seafood industries, commercial and side activities, e.g. shipbuilding (Viaroli *et al.*, 2012). Clam farming is managed by cooperatives of fishermen that access licensed areas, under the control of regional and local authorities. The extension of licensed areas and the product quantity which is daily delivered to the market are controlled by the cooperative consortia in order to guarantee both food quality and adequate revenue. For this reason, each fisherman can harvest a fixed quota that is established day by day, based on the market demand. Harvesting is performed with hydraulic dredging, which causes sediment alteration and resuspension with local effects on water quality (Viaroli *et al.*, 2003; 2010).

The deterioration of water quality has been also claimed as one of the major causes of macroalgal blooms which are often causing serious setbacks due to massive clam mortality, especially in summer (Viaroli *et al.*, 2006). To avoid anoxia the most successful intervention was and still is based on frequent canal dredging to improve water circulation within the lagoon and avoid stagnation.

Research activities in the Sacca di Goro

Water chemistry, development and control of macroalgae: The most complete and continuous water monitoring of the Sacca di Goro Lagoon was performed from 1988 to 1994 with a monthly frequency, at 8 stations, coupled in 4 homogenous sub-areas: the western corner, directly influenced by the Po di Volano, the deeper central part, the southern part, near the sand bank and the sea and the most confined eastern corner, called Valle di Gorino. Despite natural and anthropogenic modifications, and in particular the evolution of the sand bar separating the lagoon from the sea and the network of canals that was created to improve water circulation, this zonation was substantially maintained, with respect to salinity, nutrients, macroalgae, zoobenthos and the risk of hypoxia. The latter always characterized the Valle di Gorino and the central area of the lagoon, which are the areas generally invaded by macroalgae. The zone with highest nutrient and chlorophyll concentrations is that receiving the Po di Volano discharge, showing pronounced seasonal variation with winter peaks and summer minimum. Freshwaters from the Po di Volano and Po di Goro rivers are contaminated by nitrogen, especially by nitrates, which in late winter and spring attain up to 5 mg N L^{-1}, whilst phosphorus concentrations peak in summer with up to 500 μg P L^{-1}, and display average values of ~ 100 μg P L^{-1}. The nitrogen loading to the lagoon, estimated in 2–3,000 t yr^{-1}, has been considered responsible for the abnormal growth of green nitrophilous seaweeds of the *Ulva* complex and red macroalgae of the *Gracilaria* genus (Viaroli *et al.* 2006). Usually, macroalgal growth starts in the eastern shallow and most confined areas in late winter and the maximum spreading is attained in late spring. Extended *Ulva* blooms have been recorded from 1987 to 1992, in 1997–98 and more recently from 2005 to date. During the bloom peak, half of the lagoon is covered by macroalgae with biomass densities attaining 400–800 g m^{-2} as dry matter. Drifting biomasses often accumulate in the shallower areas, especially in the southern zone where clams concessions form a sort of barrier. In June–July, the sudden collapse of macroalgal mats is followed by biomass decomposition which causes anoxia, bacterial sulphate reduction and sulphide release into the water column. During neap tides and under calm wind conditions, anoxia may persist for several days, causing clams losses up to 30% of the annual production.

In order to either avoid or mitigate the impact of blooms, macroalgal biomass are harvested when attaining thick mats which cause serious threats to clams. However, the effectiveness of macroalgal harvesting seems to be low, because the harvested biomass is only a small fraction of the whole biomass bulk. This is an interesting point in terms of better linking science and management. Studies were performed in the lagoon demonstrating that to be effective the harvesting rate has to be much greater than macroalgal growth rate, which can be achieved with an optimization of the cost to benefit ratio (Cellina *et al*., 2003). Nonetheless, macroalgal harvesting is generally designed without taking into account the scientific outcomes. Together with water monitoring, research activities focused on the ecophysiology of *Ulva*. One of the main question was dealing with the capacity of the macroalgae to grow during the late spring-early summer, a period of limited N input from rivers and strong N-limitation. Another question was related to the factors determining the sudden collapse of algal blooms over large lagoon surfaces. Laboratory studies suggested that *Ulva* may incorporate nitrogen (as nitrate) during periods of high availability and store it within the thalli, a capacity that provides a competitive advantage to the macroalga (Naldi and Viaroli, 2002; Viaroli *et al*., 2005). Regarding the causes of the blooms collapse a univocal answer was not found. It is likely that multiple, co-occurring factors stress the macroalgae, including water stagnation, prolonged nutrient limitation and anoxia and sulfide toxicity. *Ulva* blooms (and collapses) were always related to external factors (as nutrient inputs from rivers) while internal sources as sediments, and in particular sediments with clams, were scarcely considered.

Biogeochemical implications of clams farming: Bartoli *et al*. (2001) evidenced by a simple incubation of intact cores collected in a control and in a farmed area, that sediments with clams can regenerate impressive amounts of inorganic nutrients to the water column and decouple oxygen consumption and carbon dioxide release. These results were basically due to the density of cultivated organisms, generally 10^3 higher that under natural conditions, and to their metabolic activity. With an upscaling procedure, it was demonstrated that mollusks farming in the Sacca di Goro deeply altered the whole lagoon benthic (and pelagic) metabolism, stimulating by a factor 1.8 and 3.3 the sedimentary oxygen consumption and carbon dioxide release, respectively. The proportionally higher stimulation of CO_2 versus O_2 fluxes suggests that the biodeposition of labile organic matter as feces and pseudofeces increases anaerobic metabolism in the Sacca di Goro and the accumulation of chemically reduced compounds within sediments. Clams excretion stimulated also at the whole lagoon scale the recycling of ammonium and soluble reactive phosphorus, by a factor 6.5 and 4.6, respectively. Nizzoli *et al*. (2006) demonstrated that clams increase also denitrification rates, but to a much lower extent as compared to inorganic nitrogen recycling, as reported by Stief (2013). From then onwards, clams farming was considered non only something to protect from dystropohic outbreaks, but also a contributory cause of the environmental problems within the lagoon.

Melià *et al*. (2003), by means of a combined experimental and modelling approach, analyzed the risk of anoxia associated to the increasing clam density. It was found that the probability to deplete oxygen in the water column was very high in summer if clams density exceeded 500 ind m^{-2}. For the first time, clams themselves were considered as possible determinants of anoxia, due to their density, to the surface cultivated over the total and to their metabolism. Results from Melià *et al*. (2003) were shared with the community of fishermen in order to suggest sustainable densities in licensed areas and avoid the risk of anoxia and product loss.

A nutrient budget was also performed in an experimental site including a control and a cultivated area (Nizzoli *et al*., 2007). Results suggest that the amount of N and P which is removed from the system with the clams biomass at the end of the farming cycle represents a very small amount if compared to that recycled to the water column via the bivalves excretion. This suggests that filter feeders do promote benthic-pelagic coupling and do favor the sedimentation of phytoplankton transported within the lagoon from either the freshwater or marine sides or produced *in situ*. In other words clams retain and concentrate phytoplankton within the lagoon, avoiding its transport to the open sea, and favor its conversion into dissolved solutes via excretion and coupled biodeposition and mineralization. Filter feeders therefore act as biological elements that remove particulate matter, retain a small fraction of what they filter in their biomass while produce large biodeposition of faeces and pseuofaeces. Direct excretion and stimulation of microbial mineralization by labile organic input result in large and balanced sediment-water fluxes of inorganic nutrients.

Bartoli *et al.* (2003) performed a simple experiment to analyze whether clams may promote macroalgal growth via phytoplankton removal and nutrient mobilization. *Ulva* thalli were grown under controlled conditions above sediment with and without *T. philippinarum*. Benthic fluxes of oxygen and nutrients were measured together with the algae net growth rates. Results from this experiment clearly demonstrated that *Ulva* was growing at significantly higher rates in the presence of clams, likely due to a combination of higher water transparency and higher supply of nutrients from sediments.

After nearly three decades of investigation it appears clear that the Sacca di Goro, besides suffering from nutrient and organic matter loads delivered by the Po River has to face relevant ecosystem modifications due to its conversion into a mollusk farm. Our recent studies have demonstrated that the presence of clams, in such densities and over such surfaces, deeply alter the benthic metabolism of the whole lagoon ecosystem. If eutrophic estuarine areas as the Sacca di Goro are naturally prone to hypoxia/anoxia, the establishment of clams farming has at least doubled the risk of oxygen depletion. Furthermore, the metabolic activity of clams and their harvesting system determine a generalized release of nutrients and pollutants stored in the sediment (Carafa *et al.*, 2007).

These statements stress that the high productivity of the Sacca di Goro is the result of a fragile equilibrium. The dry and hot summer of 2015, for example, was critical for the lagoon, with some 5,000 t of product that was lost due to algal blooms and anoxia. The farmers have created a biological buffer outside the lagoon, in deeper marine areas where young clams are maintained in case of anoxia or high temperature risk. They are also used to move large amounts of clams outside the lagoon when conditions become critical. *Ruditapes* is very robust and can tolerate such manipulations. Still, they are costly and time-consuming.

If additional areas will be exploited for the farming activity the fragile ecological equilibrium of this lagoon will be further threatened and more investment will be required for canal dredging, bottom reshaping, and management of the farmed stock, thus inducing a feedback loop/short circuit.

Conclusions

Since its introduction, the clam farming has been managed mainly with business as usual criteria, orienting the production to the maximum allowable income. This approach was possible until mid 1990s, thanks to the support of the regional and national administrations, that supported farmers with compensation for the crop loss. Following more restrictive economic policies, in the last years fisherman cooperatives have invested resources for managing the lagoon, e.g. for improving hydrodynamics, for cleaning up sediments contaminated by fecal organic matter, and for controlling macroalgal spreading.

Despite either local or international project have addressed the sustainable exploitation of the lagoon resources, a sustainable oriented farming has not yet established. One of the major research effort was performed from 2003 to 2006, within the European project DITTY aimed at implementing a scientific support system for the exploitation of southern European coastal lagoons (Aliaume *et al.*, 2007). A DSS prototype was finally operating, but only at a pilot scale, without finding a real scale application (Mocenni *et al.*, 2010).

However, this and other projects allowed to integrate ecological, economic and social issues identifying the major drivers of the lagoon ecosystem structure and processes.

Overall, environmental, economic and social issues are tightly interlinked and their balance is, in other terms, the sustainability of the whole system. Indeed, often conflicts arise among different groups of stakeholders, mainly at the local scale, with contrasting goals ranging from heavy exploitation to severe conservation. This small but complex ecosystem is also a bottleneck between the Po river watersheds and the the adjacent coastal areas. This is causing further problems for policy and decision making from local to whole watershed scales (Viaroli *et al.*, 2012)

In fact, along with internal constraints, e.g. the clam farming, the Sacca di Goro lagoon is also under the influence of the large Po river basin. Therefore management and decision-making are constrained at different administrative levels, from local to regional to the interregional (whole watershed) levels.

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