
19 Response of the Venice Lagoon Ecosystem to Natural and Anthropogenic Pressures over the Last 50 Years

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ABSTRACT

Analysis of the Venice Lagoon responses to changing morphological features, freshwater discharges, nutrient loads, fishing activities, and other factors shows that this shallow coastal water body is a complex, heterogeneous, and continuously evolving dynamic system, sensitive to an array of external drivers and pressures. Both natural and anthropogenic stressors significantly affect the lagoon system. To successfully assess the impacts of anthropogenic activities on the lagoon, it is important to understand the extent of natural variability and spatial heterogeneity. Investigations of the biotic communities, biogeochemical processes, and bottom habitats demonstrate that external drivers of change can alter the structure and function of the entire ecosystem through direct and cascading effects. Therefore, responsible governance is needed to effectively manage lagoon components, and a successful resource management of the lagoon requires an integrated vision and a participatory adaptive approach.

Key Words: Venice Lagoon, human impacts, eutrophication, climate change, benthic community responses, manila clams, *Ulva*, coastal zone management.

19.1 INTRODUCTION

Venice Lagoon is a shallow coastal water body affected by an array of anthropogenic factors. To assess the significance of anthropogenic drivers of change, it is vital to understand the extent of natural variability and spatial heterogeneity of the system. In this chapter, we review studies of the lagoon responses to major external disturbances. Results of these studies indicate the following: (1) the lagoon is a complex, heterogeneous, and dynamic system that evolves continuously in response to modifications from stressors; (2) implementation of management policies and human intervention can alter ecosystem conditions; and (3) direct effects on one or several ecosystem components influence other components, leading to changes in the ecosystem structure and function. We conclude that efficient ecosystem governance is possible and may be necessary, but given the complex nature of how the ecosystem functions, great care is required in planning any intervention. Hence, effective management of the lagoon should be an outcome of an integrated vision and an adaptive approach.

This chapter provides a historical account of the Venice Lagoon showing how human activity has affected the system for centuries. In its present condition, the lagoon is not only the result of “natural” evolution, but also of continuous active management. We focus here on recent and current development and conditions of the system. The lagoon’s morphological settings and drivers of change over the last 50 years are examined. Complementary information on the current state and observed changes over time for major ecosystem components is also provided, including details on the spatial variability of these components, which may be related to spatial gradients in pressures, such as distance from rivers or inlets, pollutant point sources, and areas of development. A conceptual scheme of the interactions between forcing factors and ecosystem components explains in part the recent evolution of the lagoon ecosystem.

19.2 HISTORICAL PERSPECTIVE

Venice Lagoon formed ~6000 years ago when sea level rise associated with the Holocene transgression led to the inundation of the present northern Adriatic Sea, creating a system of lagoons that extends along the entire northwestern Adriatic coast. Later, ~2000 years ago, this system was

segmented into separate subsystems, including Venice Lagoon (Brambati 1992). Since the first human settlement, the lagoon has been a protective barrier against invaders and an important source of food for the local population in Venice, which grew into one of the most densely populated cities in Europe in the sixteenth century.

Human impacts on the lagoon environment also increased through time via pollution inputs, fishing activities, dredging of channels, and land use changes. However, maintaining the lagoon in a healthy state and preserving the natural resources it provides has always been an important concern of the Venetian Republic. For example, fishing was strictly controlled in 1173 by the Magistratura della Giustizia (Granzotto et al. 2001), which forbade fishing activities considered damaging to the natural resources; enforced regulations on fishing gear and net sizes; restricted the sale of fish solely to fish markets to prevent escalating prices and the sale of unhealthy seafood products (Bevilacqua 1998). Industrial activities (glass, leather, fur, dye works, etc.) were regulated as of 1465, when Provveditori alla Sanità (health superintendents) enforced strict rules against air and water pollution, with relocations from the town center to islands or the mainland, and to preclude the risk of fires (Ciriaco 1995). Starting from the late fifteenth century, senators were appointed to control the misuse of the lagoon. In 1501, a special water authority called the Magistrato alle Acque was set up, with the specific task of governance of the lagoon ecosystem, especially its morphology (Bevilacqua 1998).

Venice Lagoon is a system that has undergone constant natural and anthropogenic change, and extensive efforts have been made to stabilize and preserve its morphological and ecological features. When the Venetians settled in the area, the natural tendency was for sediment infilling of the lagoon, which was enhanced by deforestation of the mainland (Ravera 2000). To slow down this trend, major rivers (e.g., the Brenta and the Sile) were diverted from the lagoon between the thirteenth and the sixteenth centuries (Figure 19.1, sites 1 to 4). Concurrently, the number of inlets was reduced (Favero et al. 1988), and the sand bar reinforced. The Venetian Republic's interventions extended even beyond the natural boundaries of the Venetian Lagoon. For example, at the beginning of the seventeenth century (1604), flow of the Po River was diverted southward through an artificial delta mouth to prevent sediment infilling of areas close to the Venetian Lagoon (Stefani and Vincenti 2005). A number of studies and monitoring programs were conducted to assess conditions, and technical alternatives were also considered. Moreover, practical solutions were provisional and had to be tested on site. A further sign of the great attention the Venetian Republic devoted to planning is that fishermen and members of the general public were invited by law to monthly conferences on the lagoon status, since these people were recognized for their valuable experiences, insights, and views on the local environment (Caniato 2005).

In the eighteenth century, the combined effects of coastal subsidence and eustatic rise in sea level increased the flooding frequency in the lagoon, and the need to protect the city of Venice from the invading sea. Sea defenses (Murazzi) were constructed along the coastal strip at the end of the century (Figure 19.1, site 5) (Campostrini 2004). Under Austrian rule and until 1934, the shape of the Lido, Malamocco, and Chioggia inlets was altered, and outer dikes were built along the sea (Figure 19.1, sites 6 through 8).

The onset of industrialization between the end of the nineteenth and the beginning of the twentieth centuries marked a new era of major anthropogenic changes of the ecosystem. Increased urbanization and land reclamation for agriculture, aquaculture, and industry reduced the total surface of the lagoon by ~3280 ha during the period from 1924 to 1960 (Ravera 2000). A major industrial area, including chemical and oil industries, was established (Figure 19.1, sites 11 through 13), leading to the dredging of new, deep navigation channels (Figure 19.1, sites 9 and 10). The industrial zone expanded over reclaimed areas (the second industrial area; Figure 19.1, site 12). Due to growing environmental concerns, a third industrial area was never built, but a large area of the lagoon had already been converted to solid land (Figure 19.1, site 13). Throughout the twentieth century, groundwater withdrawals for industrial purposes, natural subsidence, and sea level rise led to the lowering of Venice and part of its lagoon (Carbognin et al. 2004), which further increased the

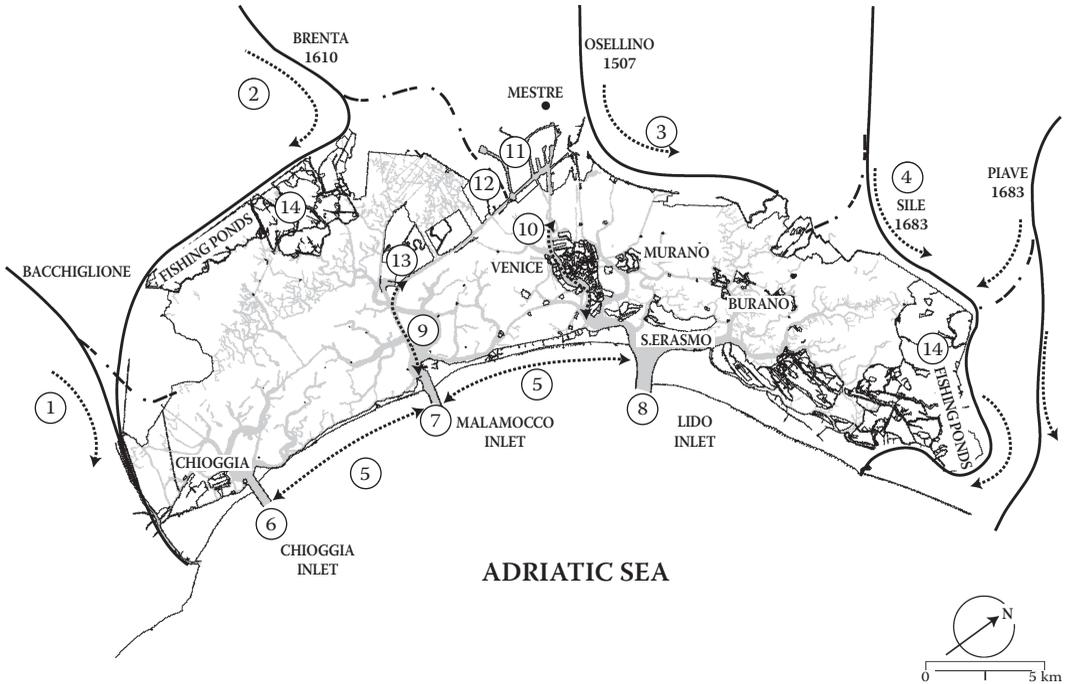


FIGURE 19.1 Schematic description of the Lagoon of Venice. Light gray indicates the network of channels, rooted at the three inlets that connect the lagoon to the sea. Areas close to water exchanges and devoted to aquaculture (fishing ponds) are in white. Dashed lines indicate original position of rivers, continuous lines the present position, after the diversion operated in the year indicated by the river name. Circles and dotted arrows indicate major anthropogenic intervention: 1 to 4, diversion of major rivers, fourteenth to seventeenth centuries; 5, fortification of coastal strip, eighteenth century; 6 to 8, modification and fortification of inlets, first half of the twentieth century; 9, navigation channel, 1960 to 1969; 10, navigation channel, 1910 to 1930; 11 to 13, land reclamation for setting up first (1917), second (1950), and third (1963) industrial areas; 14, water reclamation for aquaculture activity (vallicoltura). (Adapted from material in Quaderni Trimestrali Consorzio Venezia Nuova, www.salve.it webpage, and *Con l'acqua e contro l'acqua* CDROM.)

frequency of flooding. Concurrently, the number of fishermen and people working in the lagoon decreased sharply, and the number of city inhabitants declined to the present (~70,000) due to several causes, such as the cost of living, cost of housing, and difficulty in finding work.

19.3 ENVIRONMENTAL DRIVERS AND PRESSURES

Venice Lagoon is the largest lagoonal system in Italy, and one of the largest in the Mediterranean Sea. It surrounds the city of Venice, with ~70,000 inhabitants and an additional ~10,000,000 visitors per year. Chioggia, with ~50,000 inhabitants, and Mestre, with ~200,000 inhabitants, are also along the lagoon boundary. This is one of the most important industrial areas of Italy. Many different stressors act on the lagoon ecosystem, causing multiple environmental impacts. Among the major drivers of change there are land-based activities that deliver nutrients, heavy metals, and other pollutants; fishing (in particular clam harvesting) and aquaculture activities; other factors (e.g., groundwater extraction, subsidence, eustatism, and transportation) that affect physical and morphological features; forcing driving exchanges with the sea; and climatic conditions (Figure 19.2).

With regard to atmospheric forcing, the dominant winds are the Sirocco (from the southeast), and the Bora (from the northeast). The Bora dominates in fall and winter (Poulain and Raicich

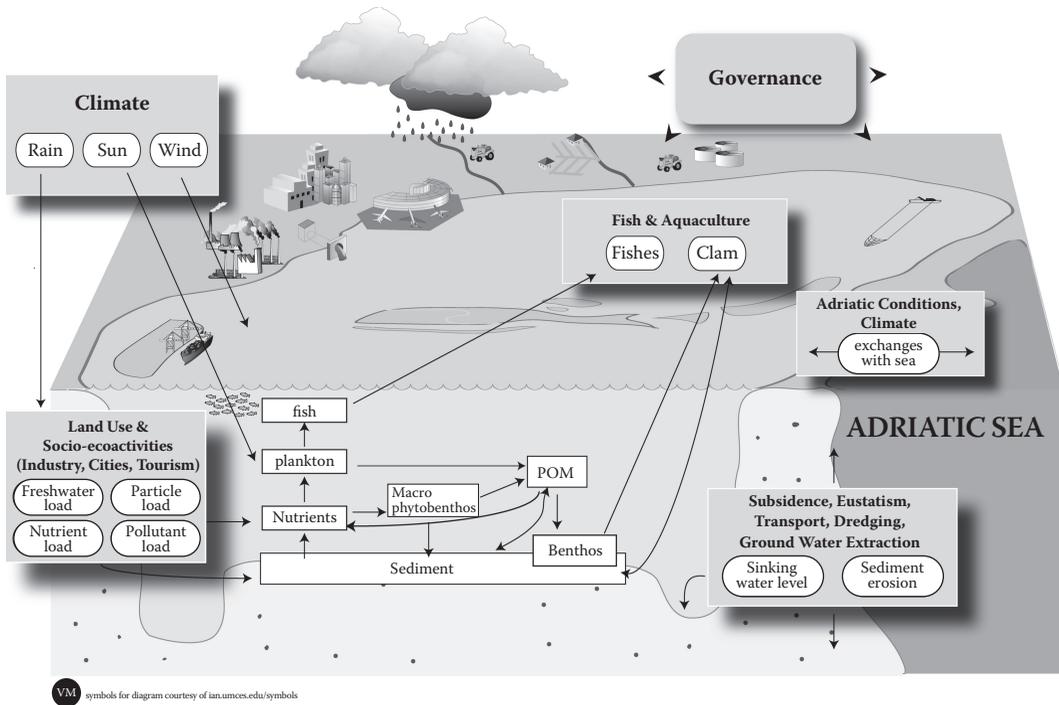


FIGURE 19.2 Conceptual scheme of major *Drivers* of changes (gray shaded boxes), related *Pressures* (white boxes within *Driver* boxes) currently acting on the lagoon ecosystem and of main relationships among lagoon ecosystem components.

2001), with speeds of over 10 m s^{-1} , though northern and northwestern winds are also observed with intensities $<5 \text{ m s}^{-1}$. Bora events tend to decrease in spring and summer, when the Sirocco becomes more frequent, blowing up to 10 m s^{-1} . Flooding events, known worldwide as *acqua alta* (high water phenomena), mainly result from a combination of tide, seiches, and easterly winds. Spring and fall are the seasons with the most rainfall, and June, September, and October the months with the least rainfall. Winter is the driest season. Water temperatures closely follow air temperatures, with a distinct seasonal cycle; minimal values occur in January, and maximal values in July. Average monthly temperatures generally range from 3°C to 24°C , but can reach 30°C and fall to 0°C (Figure 19.3).

The lagoon covers an area of $\sim 550 \text{ km}^2$, but $\sim 150 \text{ km}^2$ are used as extensive aquaculture farms and are closed to natural water exchanges. Islands cover $\sim 45 \text{ km}^2$ (Figure 19.1). A network of channels (65 km^2) rooted at the three inlets facilitates navigation and water exchange with the ocean. Islands, wetlands (generally located just above the mean sea level), and tidal flats (that have a lower elevation and are frequently exposed to air during low tides) are connected by channels. The average depth is only $\sim 1 \text{ m}$ so there is a tight coupling between pelagic and benthic environments. Decomposition processes are substantial, and biogeochemical processes accelerated.

The lagoon is characterized by a semidiurnal tidal regime with a range of about $\pm 0.7 \text{ m}$. Tidal exchanges with the sea may reach $8000 \text{ m}^3 \text{ s}^{-1}$ and typically amounts to about one-third of the total lagoon volume per tidal cycle (Gačić et al. 2004). Adriatic waters entering the lagoon are typically oligotrophic, or at most mesotrophic (Bernardi-Aubry et al. 2004; Solidoro et al. 2009). The Po Delta Plume, which sustains eutrophic conditions in the Adriatic, generally flows toward the center of the Adriatic Basin or veers southward, and only marginally affects the coastal area close to Venice Lagoon.

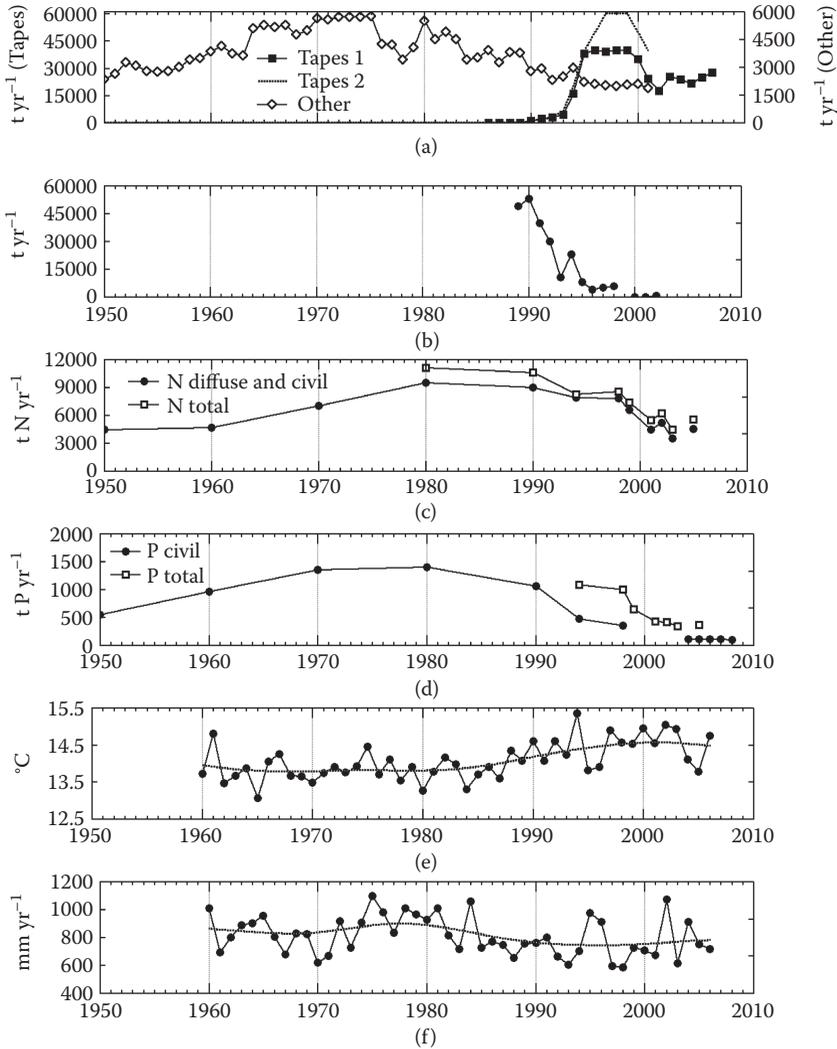


FIGURE 19.3 Multiyear time course of ecosystem drivers. (a) Two estimates of *Ruditapes philippinarum* (*R. ph.*) landing, first axis, label Tapes, and of total landing without *R. ph.* (second axis). (b) Harvested macroalgae biomass. (c) and (d) Time course of nitrogen and phosphorus loads. (e) and (f) The time evolution (and least square interpolation) of monthly mean temperature and yearly rain (elaboration of database at www.istitutoveneto.it).

19.3.1 SUBSIDENCE AND EUSTATISM

Lowering the level of the lagoon with respect to the sea increased the frequency of flooding events (Carbognin et al. 2004) and facilitated sediment erosion (Fagherazzi et al. 2006), the loss of finer sediment (Sarretta et al. in press), and the influence of marine processes (Fagherazzi et al. 2006; Sarretta et al. in press). As a result of the diversion of major rivers from the lagoon, riverine input of particulate matter has not balanced the sinking of the lagoon, which was higher from 1930 to 1970 when groundwater and natural gas were extracted from the area. Combined with a continuous eustatic rise in sea level, subsidence has further increased relative sea level rise by $\sim 1.5\ mm\ yr^{-1}$ between 1972 and 2002 (Carbognin et al. 2004).

19.3.2 FRESHWATER DISCHARGES

The lagoon receives freshwater discharges from 11 major tributaries plus several minor rivers and a number of man-regulated channels used primarily for agriculture. Freshwater discharges derive partly from rain and snow melting in the drainage basin and partly from anthropogenic control associated with agricultural use. Maximal discharges occur from October to April and are larger in the northern part of the lagoon than in the central and southern sectors. The yearly average freshwater discharge is $\sim 40 \text{ m}^3 \text{ s}^{-1}$, although pulses can be as high as $340 \text{ m}^3 \text{ s}^{-1}$, with daily values $>200 \text{ m}^3 \text{ s}^{-1}$ (Collavini et al. 2005). The drainage basin covers 2000 km^2 , mainly in the Veneto region, one of the most intensively cultivated areas in Italy; hence, rivers carry a substantial nutrient load, today roughly equivalent to 4000 t N yr^{-1} and 200 t P yr^{-1} (Cossarini et al. 2009).

19.3.3 NUTRIENT LOADS

Nutrient loads to the lagoon are generated mainly by agriculture, industrial activity, and sewage inputs. They have a positive effect on fishing and biodiversity when delivered in moderate amounts, insofar as they sustain primary production and food web processes. However, an excess of nutrients may also fuel eutrophication, which can trigger secondary effects such as hypoxia, mortality of benthic organisms, and the loss of biodiversity (Cloern 2001). Trends of nutrient loads were reconstructed by merging databases. The time series of diffuse and civil N loads and civil P loads since 1950 shown in Figures 19.3c and 19.3d were obtained by integrating the following estimates: (1) the load estimates by Bendoricchio (1998), based on population trends and agricultural/zootechnic practices (years 1950 to 1998); (2) experimental data on river inputs in 1999 (project DRAIN; Collavini et al. 2005) and in 2001 to 2005 (Arpav 2007); (3) measurements from wastewater treatment plants in the years 2001 to 2005 (Vesta 2005a, 2005b); and (4) values from Venice City (Castellani et al. 2005). By also accounting for the industrial load estimates of Bendoricchio (1998) on N in 1980 to 1998 and P in 1994 to 1998 and the measurements at Porto Marghera by Magistrato alle Acque di Venezia in the last decade (MAV 2002), one can approximate the trend of total nutrient loads into the lagoon during the last 30 years (Figures 19.3c and 19.3d). Atmospheric deposition, which was recently estimated at $\sim 1100 \text{ t N yr}^{-1}$ and 44 t P yr^{-1} by MAV (2005), is not included in the estimates of total loads. These trends show that the increased use of fertilizers in agriculture and the industrialization of the drainage basin caused a threefold rise in both phosphorus and nitrogen loads from the 1950s to the 1980s. The construction of wastewater treatment plants and the total ban of phosphorus from detergents in 1989 led to a marked reversal in the trend of phosphorus load, which has been reduced to less than half of the amount recorded in 1950. Nitrogen loads have decreased only since the 1990s, and current loads are now comparable to those of the mid-1960s (Figure 19.3), due to the introduction of nitrification/denitrification processes at the major treatment plants, to the closure of fertilizer factories, and to improved fertilization practices in agriculture (Regione Veneto 2000).

19.3.4 POLLUTANTS

Pollutants from industrial waste and other sources (e.g., drainage basins, urban areas, waste incineration, and boat engines) have been discharged to the lagoon, with a peak input during the 1960s and 1970s (Pavoni et al. 1992; Dalla Valle et al. 2005; Frignani et al. 2005), and have been accumulating in the lagoon sediments. Up to a few years ago, attention was mainly focused on heavy metals (Hg, Pb, As, Cd, Zn, and Ni), but more recently great concern has been directed toward all classes of persistent organic pollutants (POPs), such as dioxins, polychlorinated biphenyls (PCBs), hexachlorobenzene (HCB), and polycyclic aromatic hydrocarbons (PAHs). Industries are the major sources of these pollutants, which are delivered to the lagoon through point and nonpoint pollution pathways, as well as atmospheric fallout (Guerzoni et al. 2007).

19.3.5 FISHING ACTIVITIES

Fishing can have significant effects on ecosystem structure, by inducing top-down controls that change communities (Pauly et al. 1998), decreasing biomass of target species, and increasing mortality of nontarget species (by-catch). Venice Lagoon has long been exploited by small-scale fishing activities using traditional methods, while semi-industrial exploitation developed in the early 1990s targeting the Manila clam (*Ruditapes philippinarum*), an allochthonous species introduced to increase lagoon production (Solidoro et al. 2000; Granzotto et al. 2004). An analysis of landings recorded over the past 50 years (Libralato et al. 2004) indicates that the total amount of catches, clams excluded, was ~ 2000 t yr⁻¹ after World War II, which steadily increased to 5700 t yr⁻¹ by the first half of the 1970s. These statistical trends illustrate the increase in catches due to the effectiveness of new, more powerful engines and fishing devices. Successive landings decreased to less than 2000 t yr⁻¹ by 2001 (Figure 19.3). This might be due to a combination of changes in fish abundances and fishing activity, but also because of changes in the resources targeted.

The Manila clam, introduced in 1983, has been fished since the early 1990s. Landings data for this species show that the positive trend peaked in 1999, with a yearly production of $\sim 40,000$ t yr⁻¹ (and a market price of ~ 2.5 euro kg⁻¹). However, in the following 5 years, landings halved, falling in 2003 to values as low as 18,000 t (Figure 19.3a; Melaku Canu et al. in press), possibly reflecting overexploitation of the resource. Fishing vessels targeting the Manila clam use heavy-impact fishing gear (Pranovi et al. 2003), and this activity is considered to be a major cause of ecological imbalance in the lagoon, since it strongly interacts with the benthic compartment (Pranovi et al. 2003; Sfriso et al. 2003b), also contributing to the process of sediment erosion and loss from the lagoon. To allay social, economic, and ecological concerns related to open-access clam fishing (Melaku Canu et al. In press), local administrators allocated ~ 3500 ha of the lagoon in 2005 to clam farming. However, unregulated fishing still occurs.

Aquaculture has been carried out in the Venice Lagoon for many centuries in restricted areas (mainly fishing ponds termed *valli da pesca*). This is an extensive practice that has had little impact on system trophodynamics. Semi-intensive activities began during the last century, but it was only recently, after the introduction of the Manila clam, that aquaculture became a relevant environmental issue.

19.3.6 CLIMATE CHANGE

Climate change is considered a major threat to the survival of Venice Lagoon mainly because of the projected increase in sea level. However, other changes can be foreseen, the most significant being the maximal warming in the summer (up to 5°C at the end of this century under the A2 IPCC scenario), increased precipitation in the fall and winter, and decreased precipitation in the spring and summer (Salon et al. 2008), which could modify system trophodynamics (Cossarini et al., 2008). Indeed, an increase in temperature and a decrease in annual rainfall have been recorded over the last 50 years. Other direct and indirect impacts due to climate change can be hypothesized, including modification of habitats and species distribution.

19.3.7 LAGOON GOVERNANCE

Lagoon governance is an additional driver of change. For example, the issuance of regulations on land use or fishing has had far reaching effects on biota and habitats in the lagoon. The effects are mediated by both bottom-up and top-down processes. The harvesting of macroalgae standing crop during the 1980s is another example (Figure 19.3).

19.4 LAGOON STATE AND IMPACTS

19.4.1 GENERAL CIRCULATION AND CONFINEMENT

Water circulation in the lagoon is mainly tide driven (Gačić et al. 2004), but the actual pattern of residual transport (i.e., the actual motion after averaging over the tidal cycle) results from non-linear interaction of wind, basin morphology, inertial motion, and preexisting water levels inside the lagoon (Umgiesser et al. 2004). The typical residual circulation pattern consists of a large clockwise eddy around the Venice Islands and a net southward flux of water, and it indicates that the large flow of freshwater into the northern lagoon basin is balanced mainly by the outflow through the southern inlet (Solidoro et al. 2004a). Residence time varies over the lagoon and with meteorological conditions, but average values are on the order of a few days in areas close to the inlets and up to 40 days in the inner, more confined areas (Cucco et al. 2009). However, this pattern is significantly altered by the wind, which modifies circulation and increases both the water flux at the inlets and inside the lagoon (Solidoro et al. 2004a). Indeed, residence time varies significantly with wind velocity and direction. The spatial distribution of residence time and root mean square velocity in an idealized situation, computed using a finite element model specifically calibrated for Venice Lagoon (Umgiesser et al. 2004), are reported in Figure 19.4. Here, we define residence time as confinement *sensu* Guelorget and Perthuisot (1992), that is, the time required for each area of the lagoon to replace a given fraction of its volume with seawater, since this is a transport time scale indicator particularly suitable for lagoon systems.

A comparison of the general patterns of the spatial distribution of hydrodynamic properties obtained by considering real forcings (i.e., wind, tide, and water level at the inlets) supports the subdivision of the lagoon into at least three longitudinal sectors, whereas the comparison of the relative influence of the southern inlet, central inlets, and the two major channels originating in the northern inlet suggests a subdivision of the lagoon into four sub-basins. The combination of the two subdivisions yields the subdivision based on physical properties proposed by Solidoro et al. (2004a). Physical properties are also among the parameters considered by Guerzoni and Tagliapietra (2006) and Tagliapietra et al. (2009) in their subdivision of the lagoon.

19.4.2 BATHYMETRY

In the last decades, the morphological characteristics of the lagoon have changed considerably. Overall, we have observed significant erosion of sediment (Degetto and Cantaluppi 2004; Sarretta et al. in press) and a change in granulometric composition (Molinaroli et al. 2007; Sarretta et al. in press), with the loss of finer fractions. Sediment resuspension is caused by several factors, including the dredging of new large channels (Sarretta et al. in press), which altered the existing equilibrium between the channels and tidal flats, with consequent erosion of the shallow areas and infilling of the channels (Fagherazzi et al. 2006; Defina et al. 2007); an increase in the number and speed of boats, with consequent increase in waves and bottom stress (Sarretta et al. in press); a reduction in seagrass, which stabilized the sediment (Sfriso et al. 2005a,b; Marani et al. 2007); and widespread use of mechanical fishing devices for clam harvesting, which destabilized the substrate (Pranovi et al. 2004; Sfriso et al. 2005a,b). Once suspended, the finer fraction of sediment can be exported out of the lagoon (Molinaroli et al. 2007).

A comparison of the 1927, 1970, and 2002 bathymetric surveys shows that, on average, the lagoon is now ~20 cm deeper than during the 1970s and almost 90 cm deeper than during the 1930s. In addition, erosion has been more marked in the tidal flats and central basins (Sarretta et al. in press). These morphological changes are the results of sea level rise, natural and human-induced subsidence (11, 3, and 9 cm, respectively, according to Gatto and Carbogning 1981), land reclamation, dredging

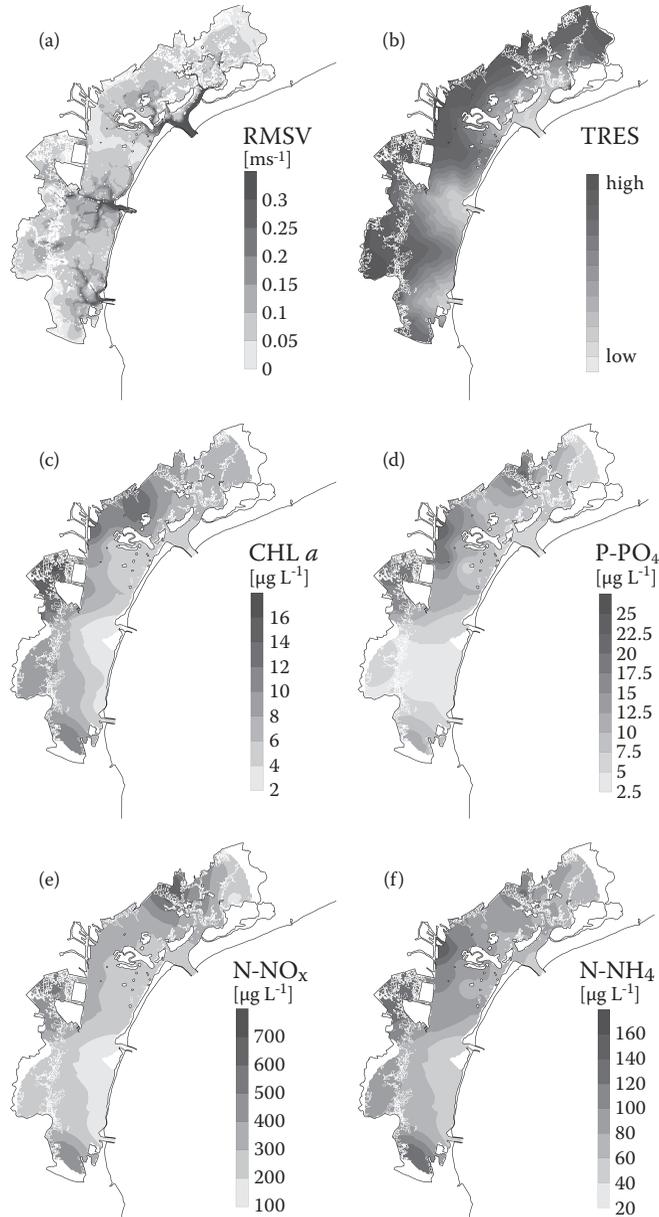


FIGURE 19.4 Spatial distribution of root mean square velocity (a), residence time (b), chlorophyll *a* (c), phosphate (d), ammonia (e), and nitrate (f). Maps (a) and (b) are obtained by numerical model simulations, (c) to (f) by spatial interpolation of experimental observation recorded in the period 2001 to 2005.

of large navigation channels including the one between the industrial area and the Malamocco inlets (site 12 in Figure 19.1) (and consequent modifications in hydrodynamic properties), and by the erosion induced by the Manila clam fishery (Sarretta et al. in press). In this regard, the increase of water level, as well as the increase of waves induced by winds and fetch, can alter the equilibrium between sediment deposition and resuspension, and promote erosion of shallow waters (Fagherazzi et al. 2006, 2007). There has been a large increase in the area covered by subtidal flats (depth between 0.75 and 2 m) from $\sim 90 \text{ km}^2$ in 1927 to $\sim 200 \text{ km}^2$ today. There is also a significant reduction in salt marshes, and a net loss of sediment amounting to $\sim 0.8 \text{ mm}^3 \text{ yr}^{-1}$ (period 1970 to 2002; Sarretta et al.

in press). The emerging picture suggests the transformation from a morphologically complex and well-developed microtidal lagoon (1927) to a simpler, deeper, flatter-bottomed, and more bay-like system (Sarretta et al. in press).

19.4.3 DISSOLVED INORGANIC NUTRIENTS

The spatial and temporal distribution of nutrients in the lagoon results from the superimposition of nutrients derived from point and diffuse sources on land, biogeochemical transformation, and exchange with the sea. Significant interannual variation exists, but long-term trends can be deduced by comparing recent observations with experimental findings obtained for a specific area (Pastres et al. 2004). Studies close to Porto Marghera, for example, illustrate how the decrease in nutrient load to the lagoon correlated with a significant decrease in nutrient concentrations (Ciavatta 2000). Datasets obtained in five different projects (Figure 19.5) indicate that over the last 40 years ammonia decreased exponentially from 5000 to 50 $\mu\text{g L}^{-1}$, while phosphorus concentrations declined from 200 to 2 $\mu\text{g L}^{-1}$. A sharp drop in phosphorus concentrations occurred at the end of the 1980s, when phosphorus was banned in detergents. Nitrogen was relatively stable between 1965 and 1995, but also decreased during the last decade. Although the decrease in nitrogen concentrations was less dramatic than those observed for other nutrients, the present nitrogen concentrations are now half of those observed around 2000.

The signal appears to be less clear in areas of the lagoon where pollutant point source inputs are less significant. A comparison of study periods in the late 1990s and late 1970s by Acri et al. (2004) showed a less sharp decline in phosphorus concentrations between the two periods and an increase in dissolved inorganic nitrogen in the central and north sub-basins. A statistically sophisticated analysis by Ciavatta et al. (2009) on a fairly homogeneous dataset covering different areas of the central basin for the period 1986 to 2006 revealed a more acute decrease in nutrient concentrations

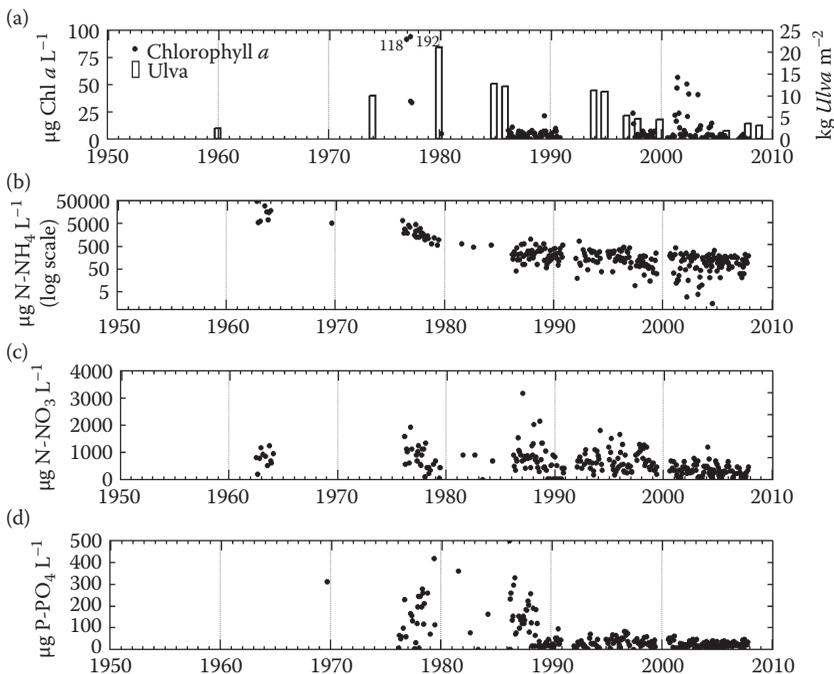


FIGURE 19.5 Multiyear time course of selected ecosystem responses. (a) Chlorophyll *a* (dots, first axis) and *Ulva* density (bar, second axis) over last 50 years. (b), (c), and (d) Evolution of concentration of ammonia (log scale), nitrate, and phosphorus, respectively.

in areas close to the nutrient point source inputs. This pattern is not as evident in areas closer to the inlets where the nutrient concentration is always lower than in the inner lagoon.

The recent nutrient status can be assessed by analysis of data collected during a 5-year-long monitoring program over 30 sampling stations during 2001 to 2003, and 20 stations during 2004 to 2005 (Solidoro et al. 2009). Figure 19.4 illustrates the spatial distribution of salinity and concentration of ammonia, nitrate, and phosphate. Maps were generated by smoothing interpolation (inverse distance to a power, quadratic law for weight computation and 0.2 smoothing parameter) of the 2001 to 2005 average values of the 20 sampling stations sampled in all periods. A decomposition of space time variability through empirical orthogonal functions shows that most of the space-time variability can be captured by a seasonal modulation of a clear spatial pattern, with a gradient of nutrients from the inner part (closer to rivers and the industrial area) toward the inlets. Indirect gradient analysis demonstrates that salinity and residence time play a major role in defining this spatial pattern (Solidoro et al. 2004b; Solidoro et al. 2009). Indeed, river signatures are clearly recognizable in nitrate and salinity distributions, indicating that tributaries represent the major sources, while industrial loads are more easily tracked from the spatial distribution of ammonia (Figure 19.4). The northern basin and the part of the southern basin close to Chioggia have the highest concentrations, while the largest fraction of the load flows into the northern basin. The concentration of phosphate today is always at a rather low level in the lagoon, possibly limiting primary productivity of the system in summer.

19.4.4 SEDIMENT NUTRIENTS

Today, nutrient concentrations in Venice Lagoon are significantly lower than in the past and are continuously decreasing not only in the water column, but also in bottom sediments. By analyzing the nutrient concentrations of 34 sampling sites of the central lagoon, it was observed that between 1987 and 2003, total phosphorus (TP) and total nitrogen (TN) in the top 5 cm of bottom sediments decreased from 386 ± 96 to $241 \pm 85 \mu\text{g cm}^{-3}$ and from 1.21 ± 9.60 to $0.71 \pm 0.27 \text{ mg cm}^{-3}$, respectively (Table 19.1). The concentrations of organic phosphorus (OP) in the bottom sediments were even greater (Sfriso et al. 2003b), decreasing from 104 ± 42 to $36 \pm 25 \mu\text{g cm}^{-3}$.

Anoxia events, a secondary effect of massive macroalgae blooms frequently observed during the 1980s over a large area of the lagoon, are no longer recorded. In addition, oxic conditions occur in the upper sediments (Sfriso and Facca 2007). Furthermore, continuous mixing of the upper sediments due to clam fishing activity likely promotes chemical oxidation of reduced compounds otherwise trapped in the sediments. An increase in resuspended bottom sediments is also evident based on sediment accumulation on sediment traps at rates ranging from 34 to 140 kg dry wt $\text{m}^{-2} \text{ yr}^{-1}$ in the 1980s to 300 to 1400 kg dry wt $\text{m}^{-2} \text{ yr}^{-1}$ in the early 2000s (Sfriso et al. 2005a, 2005b).

19.4.5 CHLOROPHYLL *a* AND PHYTOPLANKTON

Chlorophyll *a* (chl *a*), considered a proxy of total phytoplankton biomass, decreased from very high values during the 1970s (up to $190 \mu\text{g L}^{-1}$ in 1978) down to concentrations $<25 \mu\text{g L}^{-1}$ during the 1980s, and after an increase in 2000 to 2003, even lower values were recorded in subsequent years. Figure 19.4 shows that, in most of the lagoon, average concentrations of chlorophyll *a* have been below $10 \mu\text{g L}^{-1}$ since 2001. However, concentrations over the last 3 years are even lower, mostly $<7 \mu\text{g L}^{-1}$, and maximal values are rarely higher than $15 \mu\text{g L}^{-1}$ (Solidoro et al. 2009). Chlorophyll *a* concentrations follow a seasonal pattern, being highest in summer after a minor spike in spring. The intensity of summer phytoplankton blooms mainly depends on nutrient concentrations, which may be related to river discharges and the amount of rainfall during the previous weeks. Phosphorus concentrations are often very low, possibly limiting during summer in the driest years. Indeed, significant variations can occur in yearly average values of chlorophyll *a*, even if yearly average nutrient concentrations are quite similar (Solidoro et al. 2004b). Nutrients are rapidly assimilated by

TABLE 19.1
Characteristics of Major Plant Subsystems and Sediment Nutrients
in the Venice Lagoon during the 1980–2003 Period

	Past	Ulva	Ulva Decline/ Tapes Spreading	Tapes Fishing	Present	
		ha			kt	ha
Seagrasses		1990			2003	
<i>N. noolti</i>	—	4144	—	—	5	634
<i>C. nodosa</i>	—	1634	—	—	100	2946
<i>Z. marina</i>	—	3643	—	—	90	3443
Macroalgae central basin	1980	1987	1993	1998	2003	
<i>Ulva</i> SC (kt)	422	560	85	8,7	10,9	
<i>Ulva</i> NPP (kt yr ⁻¹)	1371	1 500	377	43	62	
<i>Ulva</i> GPP (kt yr ⁻¹)	8816	10 000	2 000	200	286	
Macroalgae lagoon	1980				2003	
<i>Ulva</i> SC (kt)	840	—	—	—	89	
<i>Ulva</i> NPP (kt yr ⁻¹)	2912	—	—	—	472	
<i>Ulva</i> GPP (kt yr ⁻¹)	18498	—	—	—	2335	
Sediment (top layer 5 cm)		1987	1993	1998	2003	
P tot (µg cm ⁻³)	—	386	361	375	241	
N tot (µg cm ⁻³)	—	1210	1140	930	710	

Note: Column heading “Past” refers to the period prior to *Ulva* massive blooms (before 1985); “Ulva” to the period of massive *Ulva* proliferation (approximately 1985–1990); “Ulva Decline” to the period ~1991–1995; “Tapes Fishing” to the period 1995–2002; and “Present” to the period after 2002.

Sources: Data from Caniglia et al. (1990); Rismondo et al. (2003); Sfriso et al. 2005a,b; Sfriso and Facca 2007; Facca et al. 2008.

phytoplankton in summer and generally enter biogeochemical cycles in the lagoon. In winter, however, when phytoplankton abundance is greatly reduced in the lagoon, far less nutrients enter biotic compartments and are more likely flushed out to sea than during the summer months (Solidoro et al. 2004b, 2005).

In Venice Lagoon, as in other large tidal-dominated coastal systems, the phytoplankton community exhibits high temporal and spatial variability. Therefore, it is difficult to provide an accurate representation of the system and to speculate about the long-term interannual trends of the community. However, general patterns can be delineated.

Voltolina (1975 and references therein) described the phytoplankton community in the lagoon prior to the 1980s. Spatial and temporal patterns of the community were reported for the area between the Burano wetlands and the Malamocco in 1971 and 1972. Phytoplankton abundance was as high as 10⁸ cells L⁻¹. Frequent and abundant phytoplankton blooms were recorded, which caused brown discoloration of the water. These blooms were dominated by diatoms (mainly the centric diatom *Skeletonema marinoi*, ex *costatum*) and small green flagellates, whereas other taxonomic groups, such as euglenophyceans (*Eutreptiella*), naked dinoflagellates (*Gymnodinium*), and coccolithophorids (*Calyptrosphaera*) were observed only occasionally. In the following years, plankton

abundance was generally lower, with major blooms up to 10^7 cells L^{-1} , but only in limited areas of the lagoon, usually in the inner part, where small phytoflagellates and small diatoms were commonly found. Over a 35-year period (1958 to 1992), phytoplankton primary production varied from $76 \text{ mg C m}^{-3} \text{ hr}^{-1}$ (Vatova 1960) in 1958 to $580 \text{ mg C m}^{-3} \text{ hr}^{-1}$ 20 years later (Battaglia et al. 1983). It declined to $186 \text{ mg C m}^{-3} \text{ hr}^{-1}$ in 1985 (Degobbi et al. 1986) and to $145 \text{ mg C m}^{-3} \text{ hr}^{-1}$ in 1992 (Bianchi et al. 2000). At the time of extensive macroalgal blooms in the 1980s, phytoplankton abundance was high near the industrial area and in deep channels, which were light limiting for macroalgae (Sfriso and Pavoni 1994). Phytoplankton blooms, often dominated by diatoms, were usually observed in the late winter before the increase in *Ulva* (e.g., *Skeletonema marinoi*; Socal et al. 1999), and again in May to July after the decline of *Ulva* (*Cylindrotheca closterium*; Bianchi et al. 2000). Chlorophyll *a* typically reached concentrations of $\sim 20 \text{ mg m}^{-3}$, with highest concentrations exceeding 100 mg m^{-3} (Sfriso et al. 1987, 1992; Socal et al. 1999). Some investigators noted a slight increase in phytoplankton abundance just after the decline of *Ulva* blooms (Acri et al. 2004; Socal et al. 2006), but by 2002 and for the last 10 years, phytoplankton abundances have decreased, especially in shallow or more confined areas.

During the last 10 years, a distinct increase in sediment resuspension and benthic species abundance has also been recorded (Facca et al. 2002; Acri et al. 2004). A reduction in late spring-summer phytoplankton blooms has also been documented. In terms of species composition, it can be assumed that neritic diatoms and several species of large colonial diatom species (e.g., *Chaetoceros* spp.) currently dominate microalgal populations in areas near the inlets, while mixed populations composed of chlorophytes, euglenophytes, and brackish water diatoms develop in the inner areas, with *Skeletonema* more abundant along or close to channels and resuspended benthic diatoms and cryptophytes observed in marshes (Bianchi et al. 2000). The most recent investigation to estimate phytoplankton primary production in Venice Lagoon was carried out at four stations in 2005. The minimal values were recorded in January ($<1 \text{ mg C m}^{-3} \text{ hr}^{-1}$), and the maximal values (up to $300 \text{ mg C m}^{-3} \text{ hr}^{-1}$) in July. An increasing gradient of values was observed moving from the inlet ($16 \text{ mg C m}^{-3} \text{ hr}^{-1}$) toward the industrial area (Pugnetti and Acri 2007).

19.4.6 ZOOPLANKTON

The ecological characteristics of the Venice Lagoon favor the occurrence of zooplankton species able to adapt to highly variable environmental conditions. Copepods account for about 80% of the total community (Camatti et al. 2006b), and *Acartia* is the most representative genus. *Cladocera* and other taxa can be found more frequently in the areas close to the inlets. A distinct seasonal pattern exists, roughly mirroring that of the phytoplankton, and there is a summer peak of $\sim 8,000$ individuals m^{-3} (Camatti et al. 2006b).

Changes have been observed in the mesozooplankton community structure. From the second half of the 1980s, the abundances of the more representative copepods in the Venice Lagoon, *Acartia margalefi* and *Acartia latisetosa*, decreased while during summer 1992, the copepod *Acartia tonsa*, a nonindigenous calanoid copepod, appeared for the first time in very high abundances (Comaschi et al. 1994; Camatti et al. 2006b). Currently, *A. tonsa* is an abundant or dominant species in regions of high particle concentration. It dominates the inner and middle part of the basin most of the year, occupying the original area of *A. latisetosa* and *A. margalefi* (Bandelj et al. 2008), whereas *A. clausi* is the most important taxon in the areas around the seaward inlets. *Acartia latisetosa*, a species specifically associated with brackish water, is becoming rare. Since the 1980s, the abundance of *A. margalefi* has decreased, and its occurrence in the lagoon is currently not as important as in the past (Camatti et al. 2006b). Currently, *A. tonsa* is the most representative taxon in the Venice mesozooplankton community (Acri et al. 2004; Camatti et al. 2006a), being the dominant species in quantitative terms, and accounting for more than 90% of the total zooplankton (Table 19.2). The increase in *A. tonsa* in Venice Lagoon and its absolute predominance during warm periods seems to

TABLE 19.2
Characteristics of Phytoplankton in the Venice Lagoon
during the 1970–2002 Period

	Past	Ulva	Ulva Decline/ Tapes Spreading	Tapes Fishing
	1973		1993	1998–2002
Phytoplankton abundance				
Total lagoon (10^6 cell L^{-1})	62	—	—	22
Central sub-basin (10^6 cell L^{-1})	—	—	2.6	4.4
Central sub-basin (C $\mu g L^{-1}$)	—	—	188	40
Zooplankton abundance				
(individuals m^{-3})	1970	1980	1992	2000
<i>A. margalefi</i>	850	34	9	27
<i>A. clause</i>	978	747	198	113
<i>A. latisetosa</i>	167	61	1	1
<i>A. tonsa</i>	0	0	17250	1445

Note: Column heading “Past” refers to the period prior to *Ulva* massive blooms (before 1985); “Ulva” to the period of massive *Ulva* proliferation (approximately 1985–1990); “Ulva Decline” to the period ~1991–1995; and “Tapes Fishing” to the period 1995–2002.

Sources: Data from Voltolina (1975); Facca et al. (2004a, 2004b); Camatti et al. (2006a); Comaschi et al. (1994); Sfriso and Facca (2007).

have reversed the zooplankton biomass gradient between the lagoon and sea, reflecting the greater zooplankton production in the inner area (Bressan et al. 2004).

19.4.7 MACROPHYTOBENTHOS

After the 1960s, the lagoon experienced abnormal growth of Ulvaceae, which replaced seagrass populations. There are few indications of major macroalgae blooms during the 1970s, but during the 1980s, massive blooms with densities as high as 20 kg f wt m^{-2} were regularly recorded in a large area of the lagoon, with marked effects on nutrient cycles both in bottom sediments and the water column (Solidoro et al. 1997a, 1997b; Sfriso et al. 2003b). In 1980, the macroalgal standing crop (SC), and the net (NPP) and gross (GPP) production were estimated to be 840 kt f wt yr^{-1} , 2912 kt f wt yr^{-1} , and 18,498, kt f wt yr^{-1} , respectively (Table 19.1). This condition persisted until the early 1990s, then progressively decreased (Figure 19.5), likely because of a combination of factors (Sfriso and Marcomini 1996). In 2003, macroalgae SC, NPP, and GPP decreased to 89 kt f wt yr^{-1} , 472 kt f wt yr^{-1} , and 2,335 kt f wt yr^{-1} , respectively. The macroalgae decline was particularly high in the central lagoon, where in 2003 the SC, NPP, and GPP decreased to 2.6%, 4.6%, and 3.4%, respectively, of the values recorded in 1980 (Sfriso and Facca 2007). The decline continued to 2005 (Miotti et al. 2007), then in successive years, some blooms were observed, especially southwest of Venice. However, the high biomasses recorded in the past were never observed again (Sfriso et al. 2007) (Table 19.1).

At present, the main producers of the lagoon are seagrasses. In 2003, *Cymodocea nodosa* accounted for 52% and 51% of the total seagrass SC and NPP, respectively (Sfriso and Facca 2007). This species also exhibited SC and NPP values higher than all the seaweeds combined (Table 19.1). *Zostera marina* had slightly lower values, whereas *Nanozostera noltii* accounted for only 5% and 3% of total SC and NPP values, respectively. The first studies of these seagrass species date back

to 1990 when Caniglia et al. (1990) mapped the distribution of the three main species that colonize the lagoon (i.e., *C. nodosa*, *N. noltii*, and *Z. marina*). Overall, these species covered 5493 ha in 1990 and 5431 ha in 2002 (Rismondo et al. 2003). However, despite the similar coverage, the dominance of the three species changed markedly. In 1990, *N. noltii* dominated the other species, covering 4144 ha (mixed and pure beds), but in 2002 it decreased to 634 ha. In contrast, *C. nodosa* increased in areal distribution from 1634 ha in 1990 to 2946 ha in 2002. The coverage of *Z. marina* was similar both in 1990 (3643 ha) and 2002 (3443 ha). This change in dominance seems to have been caused by several factors, the most important being the improved dissolved oxygen conditions in the lagoon for *C. nodosa*, the most sensitive species (Sfriso et al. 2007), and the reduced habitat suitability and water clarity for *N. noltii* (Sfriso and Facca 2007).

A total of ~300 species of macroalgae have been recorded in the Venice Lagoon (Sfriso and Cavolo 1983; Sfriso and Curiel 2007) and the number of species appears to be increasing, although 87 taxa (54 Rhodophyceae, 25 Phaeophyceae, and 8 Chlorophyceae) have not been found in the lagoon in recent years. Some of the newly recorded species, such as *Sargassum muticum* (Yendo) Fensholt and *Undaria pinnatifida* (Harvey) Suringar, are large species of extra-Mediterranean origin introduced into the lagoon in the early 1990s. They have colonized hard substrates of the lagoon, replacing native species. Originally inhabiting cold temperate waters, these species began to grow in winter, and in spring hard substrates of the city were completely covered by algae thalli (biomass 5 to 15 kg f wt m⁻¹) which hindered boat navigation (*S. muticum* reaches 7 to 8 m). Because these species cannot grow on soft substrates, their total biomass is limited to a few thousand tonnes, and the impact on the ecosystem is much lower than that caused by *Ulva* (e.g., during the 1980s) (Curiel et al. 2010).

19.4.8 MACROZOOBENTHOS

Analysis of available data on the macrobenthic community during three study periods over the last 70 years shows that changes occurred in the community structure between the 1990s and 2004, relative to the 1935 baseline. Species diversity sharply decreased through time, with the lowest values recorded in 1999, as indicated by Shannon index values (Table 19.3). Different trends are apparent in different sub-basins of the lagoon, with the southern sub-basin showing the most conservative pattern. The central sub-basin has exhibited the greatest changes (Pranovi et al. 2008). This pattern can be related to differences both in the structural components of the lagoon, such as the historical presence of consolidated seagrass meadows in the southern part of the water body (Caniglia et al. 1990), and the huge amount of Manila clams and the mechanical harvesting impacts, particularly in the central sub-basin (Pranovi et al. 2006). This is also reflected by an acute change in the functioning of the benthic community (Table 19.3). Data from 1935 indicate a healthier condition, with a well-diversified community, well-assorted trophic structure, and an important contribution of epifaunal species, usually characterized by high mobility. Giordani Soika and Perin (1974) referred to a remarkably impoverished benthos during the late 1950s to 1960s, with a shift toward more tolerant assemblages, a reduction in brackish species, and an increase in marine forms. The end of the 1980s was characterized by a huge biomass of benthic primary producers, dystrophic crises, and a trophic structure dominated by herbivores and detritus feeders, which by 1990 accounted for more than 55% of the total macrobenthic abundance. Then, in 1999, after the extremely successful invasion by the Manila clam, filter feeders (mainly bivalves) became dominant, accounting alone for ~50% of the macrobenthic abundance. During this period, the benthic community exhibited high secondary production, mainly due to the Manila clam (Pranovi et al. 2007, 2008).

In Venice Lagoon, as in most lagoons in the northern Adriatic Sea, distinct geomorphological zones can be recognized, including (1) inner meso-oligohaline areas close to rivers, (2) a middle mud basin characterized by low energy and sedimentation of fine sediments, and (3) marine tidal deltas around the inlets divisible into a seaward and a lagoonal component defined by ebb tidal deltas and flood tidal deltas, respectively (Tagliapietra et al. 2009; Tagliapietra and Minelli 2009).

The middle mud basin is typified by reduced hydrodynamics and more silty sediments roughly subdivided into two main parts (i.e., the shallow open waters of the central basin and the innermost part of the basin near the mainland where environmental conditions such as salinity, temperature, and dissolved oxygen are highly variable).

The near-shore areas and the ebb tidal delta are inhabited by species adapted to high salinity, high hydrodynamics, and sandy sediments with low organic content. Meadows of seagrasses, mainly *Cymodocea nodosa* and *Zostera marina*, thrive in this zone. Filter feeders dominate the benthic community here, such as the clam *Chamaelea gallina*, the razor clam *Ensis minor*, and the very abundant tellinids. Common gastropods include the muricidae *Bolinus brandaris* and *Hexaplex trunculus* and the nassarids *Nassarius mutabilis* and *N. nitidus*. Among the polychaetes, the most common species are *Owenia fusiformis* and *Arenicola marina*. Many of these species also occur in the lagoon, inhabiting the flood tidal delta area, where the razor clam *Solen marginatus* replaces *Ensis minor*, and the clam *Chamaelea gallina* declines in abundance, being progressively replaced by other venerids such as *Paphia aurea* and the Manila clam. The gastropod *Nassarius mutabilis* is replaced by other nassariids such as *Nassarius nitidus* and, to a lesser extent, by *Cyclope neritea*, which is more widespread in the inner part of the lagoon.

Filter feeders are still important in the middle basin; common bivalves are *Loripes lac-teus*, the venerids *Paphia aurea* and *Ruditapes decussatus*, and the autochthonous carpet clam, which seems to have been partially replaced by the Manila clam. The Pacific oyster *Crassostrea gigas*, introduced in the lagoon around the 1960s, is very common in this zone (Mizzan 1999). Bivalves, such as *Cerastoderma glaucum* (lagoon cockle) and *Abra segmentum*, are dominant in the innermost part of the middle mud basin. Detritivores increase in abundance in the middle mud basin where the accumulation of organic matter in bottom sediments is high. Representative detritivore species include the nereid polychaetes *Neanthes succinea* and *Hediste diversicolor*. The spionid *Streblospio shrubsolei* is also characteristic of this zone and experiences wide seasonal fluctuations in abundance (Tagliapietra et al. 1998; Maggiore and Keppel 2007).

Along inner shallow areas, where rivers enter the lagoon, *Scrobicularia plana* is commonly found. In the estuarine zone of the Venice Lagoon, *S. plana* used to be very abundant, but it has declined dramatically since the middle of the twentieth century. This decline was likely due to a

TABLE 19.3
Comparison of Macrobenthic Community Characteristics
in the Venice Lagoon during 1935, 1990, and 1999

	Past	Ulva	Ulva Decline/ Tapes Spreading	
			Tapes Spreading	Tapes Fishing
Benthos	1935	1990		1999
Shannon	2.1	1.7	—	1.1
Composition (%)			—	
Filter feeders	28	25	—	50
Herbivores	2	17	—	1
Detritus feeders	23	39	—	17
Predators	6	3	—	4
Omnivores	41	16	—	28

Note: Column heading “Past” refers to the period prior to *Ulva* massive blooms (before 1985); “Ulva” to the period of massive *Ulva* proliferation (approximately 1985–1990); “Ulva Decline” to the period ~1991–1995; and “Tapes Fishing” to the period 1995–2002.

Source: Data from Pranovi et al. (2007).

reduction in freshwater input, although the effects of pollutants cannot be discounted. The small gastropod *Hydrobia ulvae* also occurs in high density, often together with the amphipod *Corophium orientale*. In sheltered areas removed from fish predation, red larvae of the insect *Chironomus salinarius* commonly occur. In these areas, high densities of the sedentary opportunist *Capitella capitata* and other capitellids are observed as well. *Hediste diversicolor* reaches its highest densities in the intertidal zone.

19.4.9 NEKTON

A total of 79 species of fish have been identified in Venice Lagoon (Mainardi et al. 2002, 2004, 2005; Malavasi et al. 2004; Franco et al. 2006a, 2006b, 2008a, 2008b). Fish can be grouped into several ecological guilds based on species physiological tolerances to environmental conditions, type of migratory behavior, and reproductive mode. These include: (1) lagoon residents (LR), which spend their whole life cycle (or most of it) in the lagoon environment; (2) marine juvenile migrants (MJ), which spawn at sea and utilize the lagoon as a nursery; (3) marine seasonal migrants (MS), which regularly enter the lagoon environment, mainly in late spring-summer to take advantage of the high abundance of prey; (4) marine occasional visitors or stragglers (MO), which are marine spawners (stenohaline species) only occasionally found in the lagoon; (5) catadromous (MC) and anadromous (MA) migrants, which use lagoon waters mainly as pathways for ontogenetic migration between the sea and fresh water and vice versa; and (6) freshwater species (FW) (Malavasi et al. 2004; Franco et al. 2006a, 2008b).

Marine stragglers are the most abundant guild with 32 species, followed by marine migrants (i.e., MJ, MS, and MC) with 24 species, and lagoon residents with 17 species. Significant seasonal variations have been observed, including a progressive increase in species richness, total abundance, and biomass during spring as a result of both the immigration of individuals from the sea and the recruitment of resident species, a summer peak, and a decrease during late fall (Malavasi et al. 2004, 2005; Franco et al. 2006a, 2006b). On an annual basis, lagoon residents account for ~90% of the total fish abundance, whereas the euryhaline species (MJ and MS in particular) account for just 6.2%.

The fish assemblage in seagrass beds is dominated in numerical abundance by resident species such as the sand smelt *Atherina boyeri*, the grass goby *Zosterisessor ophiocephalus*, and the pipefish *Syngnathus abaster*, *S. typhle*, and *Nerophis ophidion*. The seagrass meadows provide temporal stability to the assemblage during the year, which is not characteristic of the fish fauna in other habitats (Franco et al. 2006a, 2006b).

In mudflats and tidal creeks, small-sized resident species are abundant, such as the gobies *Pomatoschistus marmoratus*, *P. canestrinii*, and *Knipowitschia panizzae*, and the pupfish *Aphanius fasciatus*. Marine migrant species (e.g., *Engraulis encrasicolus*, *Platichthys flesus*, *Solea solea*, *Liza saliens*, and *Pomatoschistus minutus*) are also well represented in these habitats.

In barren or sparsely vegetated sandy bottom habitat areas, the fish fauna is generally less abundant. Here, the most common species are widely distributed residents, such as *A. boyeri* and *P. marmoratus*, and marine migrants (including marine juveniles).

19.4.10 LANDINGS DATA

Data on nekton community composition over time are generally lacking, but data compiled on artisanal catches might provide a proxy for such trends. However, we must be cautious when interpreting this kind of data because not all species are fished, and because changes in landings also stem from changes in fishing effort and other activities, market values of target species, and market demand. Using market data corrected for unofficial landings for the years 1945 to 2001, it was possible to pinpoint differences in catch composition in terms of trophic guilds (Libralato et al. 2004),

TABLE 19.4
Composition of Major Biotic Groups in the Venice Lagoon Landings

Landings (%)	Past		Ulva	Ulva Decline/ Tapes Spreading	Tapes Fishing
	1945–1960	1961–1984	1985–1989	1990–1995	1996–2001
Predators	0.08 (0.03)	0.06 (0.03)	0.12 (0.03)	0.03 (0.05)	0.29 (0.06)
Detritivorous	0.13 (0.03)	0.14 (0.03)	0.15 (0.01)	0.16 (0.01)	0.21 (0.04)
Plankton feeders	0.16 (0.02)	0.26 (0.05)	0.22 (0.03)	0.17 (0.03)	0.09 (0.03)
Benthic feeders	0.11 (0.05)	0.13 (0.04)	0.16 (0.04)	0.16 (0.04)	0.1 (0.03)
Cephalopods	0.15 (0.04)	0.21 (0.06)	0.24 (0.04)	0.37 (0.11)	0.21 (0.03)
Shrimps	0.11 (0.03)	0.07 (0.06)	0.03 (0.01)	0.02 (0.02)	0.02 (0.01)
Crabs	0.26 (0.07)	0.12 (0.03)	0.08 (0.04)	0.09 (0.04)	0.08 (0.02)

Note: Column heading “Past” refers to the period prior to *Ulva* massive blooms (before 1985); “Ulva” to the period of massive *Ulva* proliferation (approximately 1985–1990); “Ulva Decline” to the period ~1991–1995; and “Tapes Fishing” to the period 1995–2002. Table gives average landing proportion and standard deviation (in parentheses).

Source: Data from Libralato et al. (2004).

whose averages for relevant periods are reported in Table 19.4. A steady increase in the proportion of detritivorous fishes (mainly Mugilidae) from 13% to 20% of the catches is observed. Concurrently, the proportion of scavenger crabs (mainly *Carcinus aestuarii*) and shrimps (mainly *Palaemon* sp. and *Crangon crangon*) decreased steadily from 26% to 8% and from 11% to 2%, respectively. Benthic feeder fishes, mainly Gobiidae, accounted for 11% of the landings before the 1960s, and then increased up to 16% during the *Ulva* and post-*Ulva* period. They subsequently declined to 10% of the landings during the extensive clam exploitation period (1996 to 2001). Plankton feeders, mainly *Atherina* sp. and *Engraulis encrasicolus*, accounted for 15% of the landings during the period 1945 to 1960 and then increased to 26% during the period 1961 to 1984. Plankton feeders decreased progressively from 22% to 17%, and to 8% during the following periods: 1985 to 1989, 1990 to 1995, and 1995 to 2001, respectively. Landings are also characterized by a sharp increase in piscivorous fishes (mainly *D. labrax*): 8% of the catches in 1945 to 1960, and 29% during the last period 1995 to 2001. Cephalopods (*Sepia officinalis*, *Loligo vulgaris*) comprised 15% of the landings during the period 1945 to 60, and then progressively increased up to 36% during the period 1990 to 95. This guild now accounts for ~21% of landings (Table 19.4).

19.5 ECOSYSTEM RESPONSES

The Venice Lagoon is a large, open system subjected to natural and anthropogenic stressors, and characterized by highly heterogeneous morphological structure and variable physicochemical (Molinarioli et al. 2007; Cucco et al. 2009), biogeochemical (Solidoro et al. 2004a, 2004b), and biological (Occhipinti Ambrogi et al. 1998; Malavasi et al. 2004; Franco et al. 2006b; Guerzoni and Tagliapietra 2006; Marchini and Marchini 2006; Bandelj et al. 2008, 2009; Tagliapietra et al. 2009) conditions. It can be subdivided into four sub-basins typified by internal, intermediate, and pseudo marine areas (Figure 19.6) (Solidoro et al. 2004b; Marchini and Marchini 2006; Bandelj et al. 2008, 2009; Sfriso et al. 2009; Tagliapietra et al. 2009). These sub-basins can be further subdivided into smaller geographic units, reflecting the environmental heterogeneity of a system comprised of closely interconnected, mutually interacting habitats (Tagliapietra and Volpi Ghirardini 2006; Tagliapietra et al. 2009).

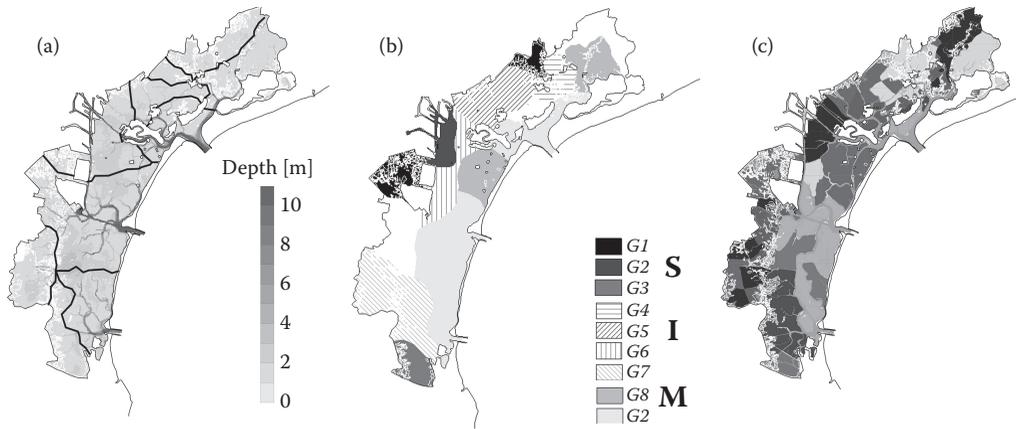


FIGURE 19.6 Lagoon partitions based on: (a) physical, (b) biogeochemical properties, and (c) morphological. Physical partition is based on confinement time and longitudinal subdivision in four sub-basins. The figure also reports bathymetry. Biogeochemical partition (b) is derived by subjectively drawing boundaries among nine groups which result from multivariate analyses (cluster and ordination methods) on data from 2001 to 2005; boundaries are drawn for visual clarity and have no objective physical meaning. (Adapted from Solidoro et al. 2004b). Landscape classification (c) subdivides lagoon based on geomorphological, hydrodynamic, and sediment properties. (Adapted from Guerzoni and Tagliapietra 2006).

The lagoon exhibits multifaceted responses to natural and anthropogenic forcing factors. The availability of a long-term time series of data also enables us to synthesize and integrate these covariations as well as to assess the causal relationships among the drivers of change on the ecosystem and their direct and indirect effects. This information also allows us to develop a conceptual scheme of ecosystem evolution over decades of time.

Industrial and agricultural activities grew exponentially from the early 1940s to the 1960s. They greatly impacted the lagoon ecosystem. For example, there was a direct impact of pollutants discharged into the lagoon, which are still present in bottom sediments and can bioaccumulate in the food chain (Pavoni et al. 1992; Dalla Valle et al. 2005; Frignani et al. 2005). Therefore, pollutant contamination and, in particular, bioaccumulation of organic pollutants remains a concern, with “hot spots” of sediment contamination in the industrial channel sediments up to 2500 ng I-TEQ kg^{-1} dw (Guerzoni and Raccanelli 2004; Guerzoni et al. 2007). Studies of contaminants in the system (Raccanelli et al. 2004; Micheletti et al. 2008) suggest that bioaccumulation of POPs in lagoon organisms may be significant. These conclusions have important implications both in terms of risk to human health (Frangipane 1999; Raccanelli et al. 2008) and an increase in natural mortality and/or energy expenditure for metabolic detoxification in lagoon species. These topics have been reviewed elsewhere (Orio and Donazzolo 1987; Guerzoni and Raccanelli 2004; Carrer et al. 2005; Guerzoni et al. 2007; Micheletti et al. 2008).

Industrial activities have also caused a number of indirect impacts on the lagoon. Aside from land reclamation and associated habitat loss, industrial activities have been responsible for dredging of large navigation channels that altered the morphological balance between the channel and tidal flats and permanently modified a large part of the central basin. They have also led to the extraction of groundwater and natural gas, causing an increase in the rate of lagoon subsidence. The diversion of fresh water for agricultural and zootechnical uses, together with the deepening of the inlets, the building of jetties, and digging of new channels, have resulted in intrusion of seawater, leading to expansion of the central mud habitat at the expense of estuarine-like oligohaline habitats, already drastically reduced by the diversion of the majority of rivers to the sea in previous centuries. These alterations of geomorphological and physical properties clearly impacted the spatial distribution, structure, and composition of the macrobenthic community in the lagoon between the late 1950s

and 1960s, as evidenced by a marked impoverished community, a replacement of brackish species with more marine ones, and a shift toward assemblages that are more tolerant of eutrophic conditions (Giordani Soika and Perin 1974).

An exponential increase in the use of fertilizers, together with pollutants from industrial areas, contributed to an acute, continuous increase in nutrient loads emitted to the lagoon from the drainage basin (Figure 19.3). The increase in nutrient loads correlated with increased nutrient concentrations in the lagoon (Figures 19.2 and 19.3). Eutrophication, together with the modification of hydrodynamic and morphological features, favored the occurrence of massive macroalgae blooms dominated by *Ulvacea* during the 1980s. These blooms impacted nutrient cycles and the benthos. Indeed, in late spring and summer, macroalgae beds covered almost all shallow areas where water movement was low and residence time high, causing substantial depletion of the nutrient pool in the center of the beds and triggering the start of anoxic events. These events caused an increase in *Ulva* mortality and the amount of decaying organic material on the lagoon floor, resulting in additional consumption of oxygen and worsening of the anoxia, which rapidly spread from bottom sediments to the water column over large areas (Sfriso et al. 1992; Solidoro et al. 1997a). Among the more serious effects of the dystrophic crises was the release of hydrogen sulfide that adversely affected human activities in Venice and other surrounding land areas (Ravera 2000). Dystrophic crises also had significant impacts on the lagoon ecosystem, influencing biogeochemical cycles, promoting the release of large amounts of nutrients, enrichment of organic matter in bottom sediments, and secondary impacts on the benthic community (Solidoro et al. 1997a, 1997b). Subsequent decreases in shrimp and crab landings might also be coupled to this series of changes (Sfriso et al. 1992; Sfriso and Marcomini 1996). *Ulva* mats acted as traps for nutrients entering the lagoon, storing them in plant tissue. In summer, even nitrogen in waters entering from the Adriatic fueled macroalgal growth (Sfriso and Marcomini 1996).

The large biomass of *Ulva* caused a sharp decrease in other seaweeds as well as a reduction in phanerogams (Sfriso et al. 1987), while herbivorous and detritivorous species dominated the macrobenthic and nektonic communities. In addition, phytoplankton density decreased, with blooms occurring only in those areas where the macroalgae density was not very high. Typically, a spring phytoplankton bloom was triggered before the macroalgal blooms (Sfriso et al. 1992; Solidoro et al. 1997a), and other plankton blooms followed *Ulva* dystrophic crises, fostered by nutrient released during *Ulva* decomposition. The major shift in zooplankton composition, with occurrence of *A. tonsa*, can be regarded as an additional indicator of eutrophic conditions.

In order to mitigate eutrophication, several policy measures were enforced, including environmental legislation issued to specifically address environmental problems in Venice Lagoon. Harvesting of macroalgae standing crop was conducted, which removed up to 60,000 t of plant matter per year from the lagoon during the 1980s (Figure 19.3b). The effectiveness of the new regulations was evidenced by the decrease in nutrient concentrations in the system, particularly phosphorus, which dropped to very low levels after the enforcement of a total ban on phosphorus in detergents in 1989. However, the decline in *Ulva* biomass, observed during the 1990s, was probably due to a combination of factors, which triggered the system to shift to an alternative regime, then maintained by several co-occurring factors. Adverse meteorological conditions at the beginning of the 1990s probably played a very important role, with several consecutive, longer than usual cold seasons, which reduced over-wintering of the macroalgae. Other important factors were increased turbidity and sedimentation of particulate matter on *Ulva* thalli, which hindered macroalgae growth during more productive seasons (Sfriso and Marcomini 1996). The subsequent reduction in laminar free-floating thalli initiated a positive feedback by favoring wind- and tide-induced sediment resuspension, further increasing water turbidity and reducing photosynthetic activity. The drop in biomass standing crop reduced the frequency of anoxia to only episodic events, thereby enabling the establishment of zoobenthic grazer populations to exert greater control on *Ulva* biomass. Together with harvesting of macroalgae standing crops, these processes were effective in keeping the total

macroalgae biomass at a much lower level than in previous years when it reached a total wet weight as high as 10^7 t.

The beginning of massive fishing of *Ruditapes philippinarum* between 1995 and 2000 (Figure 19.3), often by means of illegal fishing devices (hydraulic dredges), greatly disturbed bottom sediments, causing direct damage to the macrophytobenthos and a further increase in sediment resuspension, thereby hampering recolonization by *Ulva* and contributing to further reduction in *Ulva* biomass. As a result, the distribution of the Manila clam spread throughout the area free of macroalgae. New macrophyte recolonization appears to have been precluded by fishing activities and related impacts on the lagoon floor (Sfriso and Marcomini 1996; Sfriso and Facca 2007). Other important factors that presently control macroalgae growth are sediment resuspension due to the morphological works used to reinforce tidal lands, and the ongoing oligotrophication of the lagoon in recent years.

Following the decline in seaweed abundance, nutrients entering the lagoon were no longer readily trapped by plant uptake and could be exported to the sea without being removed by photosynthetic activity. In addition, the flux of organic matter to bottom sediments was greatly reduced. In the case of *Ulva*, therefore, biomass removal helped counterbalance sediment enrichment. In the case of *Ruditapes*, which feeds on particulate matter, harvesting promoted the effective consumption of organic matter stored in the sediments through resuspension. During the first phase of *Ruditapes* colonization, when fishing pressure was not yet very high, clam growth and metabolism facilitated the transfer of organic matter from the water column to bottom sediments, which was consequently enriched. In the following phase, however, heavy clam fishing caused the transfer of organic matter from the water column and sediments to the clams with export from the system, resulting in impoverished sediment. Clearly the demographic explosion of the Manila clam and its commercial exploitation has greatly altered the macrobenthic community, with a shift toward infaunal species and loss of more fragile or less mobile species due to the pressure exerted by mechanical fishing gear.

The decline in nutrient contents observed in lagoon bottom sediments, along with declining nutrient loads, caused a reduction in nutrient concentration, phosphorus in particular, in the water column. Chlorophyll *a* values have declined as well, probably due to a combination of bottom-up (resource limitation) and top-down (clam filtration) controls. Between 2000 and 2003, a temporary increase in chlorophyll *a* values was noted possibly because of a reduction of clam landings (Figures 19.3 and 19.5), but since 2004, only rather low levels of chlorophyll *a* have been recorded. In the last two decades, there has been a reversal in the eutrophication trend of the system.

Climate change is another major threat to the Venice Lagoon. Atmospheric temperature and sea level rise are predicted to increase significantly over the next 50 to 100 years, which will lead to greater frequency of flooding. According to Gambolati et al. (2002), extensive areas of the western part of the northern Adriatic Sea coastline could be permanently lost by 2100. In order to mitigate the impact of flooding on the city of Venice, specifically designed mobile gates (i.e., the MOSE system) are now being set in place, and will be operated to temporarily close lagoon inlets concurrently with high tide events (www.salve.it). The consequence of this intervention has been long debated because of possible adverse effects on the lagoon ecosystem. Modifications made in areas near the inlets to install the gates, and repeated temporary closures, may or may not alter the lagoon ecosystem, but it is clear that, if the frequency of closures will be so high as to significantly modify morphological and hydrodynamic properties, biogeochemical and food web processes could change significantly as well. Even considering less extreme scenarios, regional climate models indicate for the period 2070 to 2100 a significant increase in air temperature, up to 3°C (5°C in summer), and changes in the temporal pattern of rainfall over the Venice drainage basin (Salon et al. 2008).

Aside from the obvious direct effects of air temperature increase on water temperature and organism metabolism, climate change might impact the lagoon ecosystem by inducing changes in the levels and dynamics of seston and biogeochemical properties. Results obtained in a downscaling experiment confirm that the annual mean rainfall will not change appreciably in the watershed

of the Venice Lagoon, whereas the seasonal patterns will likely change, with summer and spring becoming drier and winter and fall wetter (Salon et al. 2008). These changes will potentially increase winter nutrient concentrations. However, the annual planktonic primary and secondary production of the Venice Lagoon will decrease, and nutrient surplus will be exported to the Adriatic Sea (Cossarini et al. 2008). The food web structure, notably higher trophic level organisms, could be adversely affected. In addition, the success of aquaculture activity of *Ruditapes philippinarum* could be significantly impacted (Melaku Canu et al. in press).

19.6 CONCLUDING REMARKS

The Venice Lagoon is a large, complex system affected by multiple natural and anthropogenic forcing factors, and characterized by high heterogeneity in physical, biogeochemical, and biological conditions, of mutually interacting habitats. An array of stressors has altered morphological settings, biogeochemical properties, and biological components of the ecosystem either directly or through cascading effects. For example, morphological modifications of the basin, reduction of freshwater inflow, increase in nutrient loads, fishing activities, and aquaculture operations have all impacted the structure and function of the ecosystem through time. Harvesting of the Manila clam has directly affected the benthic community and also caused cascading effects such as the loss of sediment, increase in turbidity, and removal of organic matter from the system. In the past, the lagoon has been plagued by serious eutrophication problems, but in recent years, these problems have been mitigated, and the system is now in a state of progressive oligotrophication. In the future, however, rising sea level coupled to warming climatic conditions will have an increasing impact on human habitation in the region due to greater frequency of flooding and other adverse effects.

The lagoon is a continuously evolving system that responds rapidly to human activities. As such, the long-term health and viability of this important system is contingent upon sound and effective coastal zone management, which should be an outcome of an integrated vision and a participatory and adaptive approach (Suman et al. 2005). Given the complex nature of how the ecosystem functions, great care is required in planning any intervention.

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