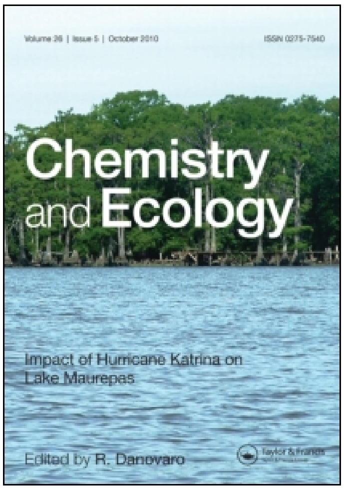

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The Ligurian Sea: present status, problems and perspectives

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The Ligurian Sea: present status, problems and perspectives

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The Ligurian Sea is a deep basin in the northernmost sector of the western Mediterranean which shows peculiar hydrodynamic and meteo-oceanographic features. The coasts of the Ligurian Sea are among the most urbanised and industrialised along the Italian coastline: the main causes of disturbance being littoral urban development and harbour activities, the building of littoral rail- and highways, and the presence of several polluted discharges. This review, by evaluating the huge scientific output published in the last three decades, describes and discusses the most important geological, hydrological and biological characteristics of the Ligurian Sea. We show that this regional sea has largely been investigated in terms of its geological and structural evolution, as well as in terms of the sedimentation dynamics of the littoral and deep bottoms, with particular attention to the sedimentation balance of the beaches and their erosive processes. We report that the prevalent hydrodynamic and meteo-oceanographic conditions favour a continuous exchange of coastal water masses, and that the seasonal and interannual dynamics of water masses can effects the local climate, with direct and indirect consequences on fish and benthic communities documented in the last decade. We stress that although recent studies offer good knowledge of the distribution of coastal benthic communities, only scant information is available for the whole continental shelf, the submarine canyons and the rocky bathyal bottoms. Our meta-analysis reveals that significant fishing activities are monitored, but also that certain sectors of the biological resource are suffering, and suggests the set up of appropriate management measures. The Ligurian Sea hosts a number of Marine Protected Areas (MPAs) of high relevance, while the institution of the Whale Sanctuary completes the protection policy of the Regione Liguria. Our meta-analysis points out the need for long-term studies, based primarily on the analysis of those areas of the Ligurian Sea that have been little investigated to date. Finally, only properly addressed studies, using experimental approaches and along appropriate spatial and temporal scales, might allow us to understand the functioning of the Ligurian marine ecosystems, evaluate their health conditions and the dynamics of the main variables that affect the distribution of the single species (including species of high economic value) and benthic communities.

Keywords: Mediterranean Sea; Ligurian Sea; geomorphology; hydrology; plankton; benthos; necton; fisheries; biodiversity; introduced species; Marine Protected Areas; environmental policy

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1. The Ligurian Sea: geomorphological and sedimentological features

The Ligurian Sea is the northernmost sector of the western Mediterranean, bordered to the west by the Gulf of Lion and the Algero-Provençal Basin, and to the east by the northern Tyrrhenian Sea and the Corsica Channel.

The Ligurian basin consists of the northern portions of two distinct geological systems, of different origin and evolution. The western part is deep, reaching >2600 m and oriented along a NE–SW axis, consists of a very thin continental crust and follows the Oligo-Miocene rotation of the Sardinia–Corse block. The eastern part, located east of a seamount area and the seaward extension of Cape Corso, consists of a sedimentary cover of notable thickness, accumulated following the post-Tortonian distensive tectonics of the northern Tyrrhenian [1].

This very particular geodynamic context has produced complex structural interactions between the two systems, which currently overlap in the Gulf of Genoa [2]. The western and eastern basins of the Ligurian Sea differ in physiography, amplitude and the steepness of their continental margins, in the specific evolutionary trends of their faulted rocky substrate, in their relative sedimentary coverage and subsidence processes and, finally, in the effects of neotectonics (Figure 1).

The Alpine Margin is characterised by narrow continental shelves and steep slopes cut by several canyons, often lying on the tectonic lines between different evolutionary sectors. The Corse Margin has similar features, but differs from the Alpine Margin in that its lower sedimentary load, as the shelf–slope system, bypasses the slope and arrives directly on the bathyal plain of the Ligurian Basin. In fact, the depocentre of the sediments is situated at the foot of the Ligurian slope, where

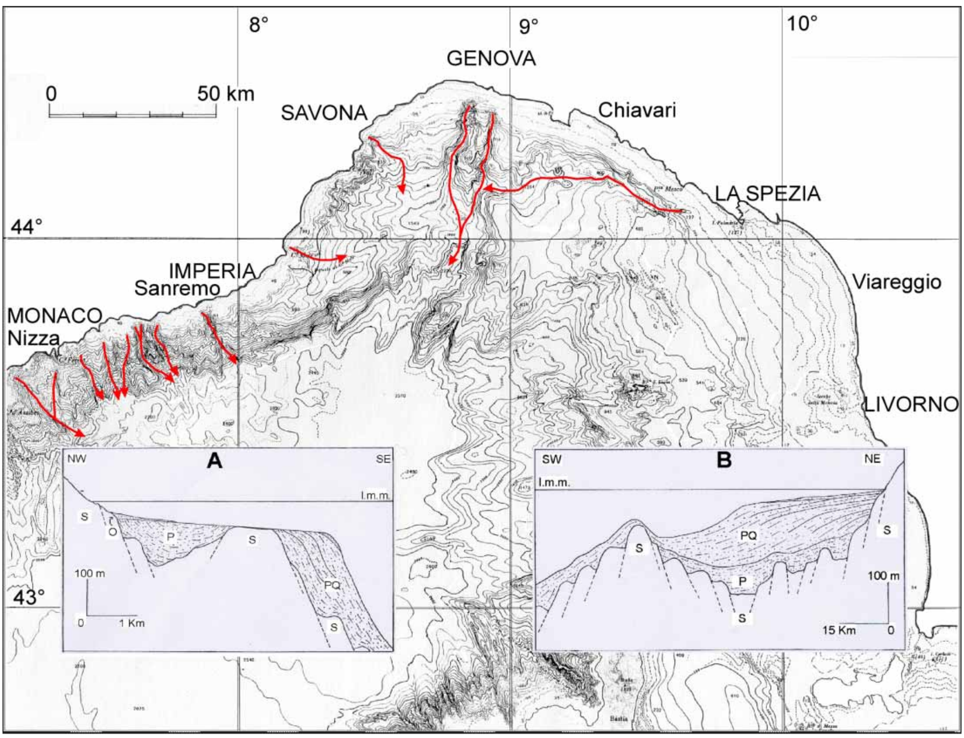

Figure 1. Physiographical characteristics of the Ligurian Sea. Alpine (A) and Apenninic (B) continental shelf model. The axes of the main canyons are also reported. S, substrate; P, Pliocene sediments; PQ, Plio-Quaternary sediments; O, Holocene sediments (from map n. 1250, ed. 1960, by Istituto Idrografico della Marina, authorisation n. 12/88, 18.7.1988).

there are important coalescent marine conoids (deep sea fans), with important distribution systems and turbid sedimentary accumulations on the continental rise.

Instead, the Apenninic Margin, lying to the east of the sea mount area and the seaward extension of Cape Corso, consists of a well-developed platform and a gentle slope, cut off from the deep plain by other structures.

The continental shelf is similar in both Ligurian sectors because the substratum, which deepens in a distensive mode from the continental margin, is almost completely covered by sedimentary deposits accumulated over the last 2–3 million years and reworked by repeated transgressive–regressive cycles related to glacioeustatic variations in the sea level. The sediments that have filled the depressions were caused by progradational processes along the shelf break due to the erosion, which is still taking place, of the 'young' Alpine and Apennine chains, moving vast quantities of terrigenous material towards the Ligurian Basin.

This sedimentary evolution of the continental platform mainly occurred during the Plio-Quaternary, even though early Miocene erosive remodelling can be detected in some areas. The Quaternary glacioeustatic cycles have created the present-day morphology of the shelf as periods of high sea levels have favoured aggradation and/or progradation processes of the sedimentary cover and erosive events have generated important truncations within the sedimentary series and produced progradant structures along the shelf break (Figure 2).

Structural conditioning and the heavy sedimentary load have influenced both past and current sedimentary processes. These phenomena can be attributed to increases or decreases in the sedimentary budget related to the glacioeustatic cycles, which, having a different erosive capacity from the agents of exogenous processes and sea levels, have dispersed the sediments over a large area and deposited them alternatively on the shelf and slope. The seismotectonic instability of the

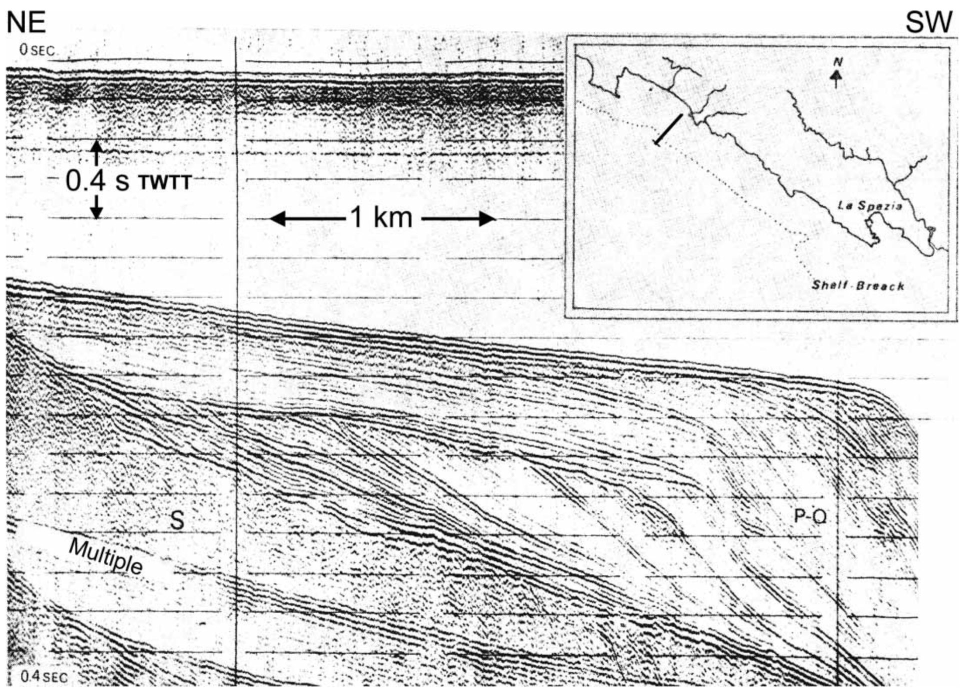

Figure 2. Sestri Levante (Genoa) continental shelf Air-Gun seismic line. The geophysical section shows the acoustic substrate (S) and the Plio-Quaternary sediments (PQ). The seismic stratigraphy shows some unconformities which separate different sediment bodies because of sea level variations.

slope and margin (Figure 3) has caused considerable sedimentary mobility along the slope and submarine canyons.

Such depressions, the consequence of tectonic and erosive processes, have led to the accumulation of notable sedimentary masses caused by turbidity currents at the foot of the slope, and to catastrophic movements that can cause tsunamis, the most recent of which, in 1979, ravaged the coast between Nice and Antibes [3].

Gravitative processes of diverse origin and dynamics along the inner slope of the Gulf of Genoa (Figure 4) and the Alpine sector of the Ligurian Basin (Figure 5) have deposited sediments on the wider and older sedimentary apparatus of the 'Ligurian Fan'.

The canyons, often carved into the lower bathymetries of the continental shelf, not only play a role in the gravitative movement of the sediments, but are also sites of important currents that sometimes favour the rise or sinking of the water masses [4].

Geomorphological, sedimentological and seismo-stratigraphic studies have been conducted on the continental shelf [5] to define the depositional stratigraphy and to characterise the bottom sediments, allowing the localisation of sandy and gravelly deposits which could be used to nourish beaches undergoing erosion (Figure 6).

Off the Portofino Marine Protected Area (MPA), geomorphological, geophysical and sedimentological information is available for the coast and inner shelf, and for the seafloor and its recent evolution as a result of glacioeustatic changes, particularly those of the last 20,000 years (Figure 7). Moreover, detailed morpho-bathymetric data are available for the head of the Levante

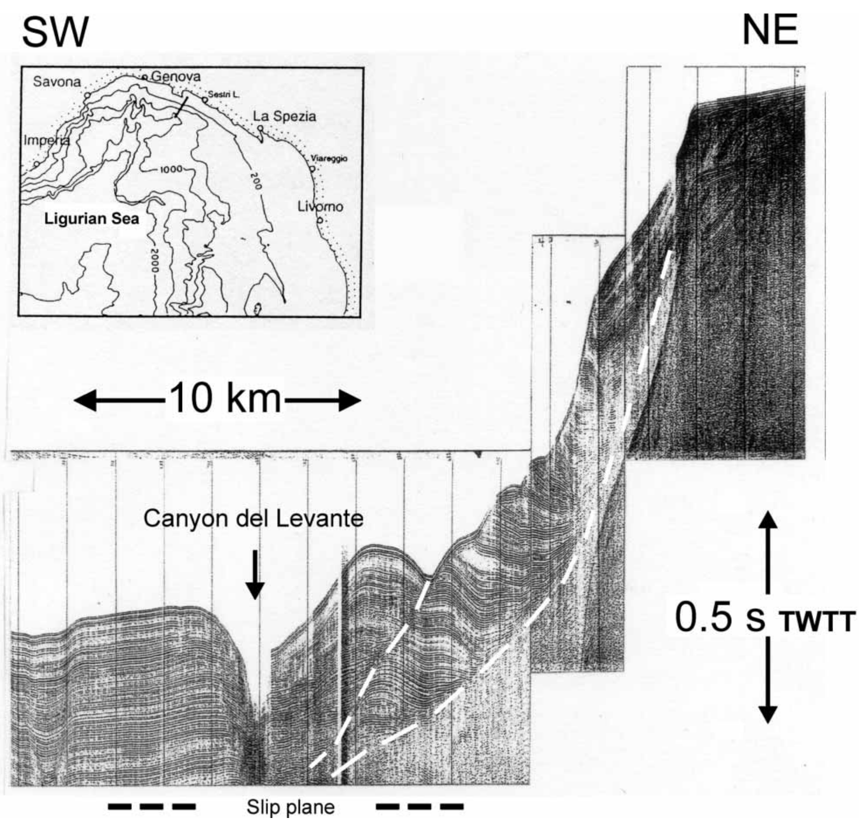

Figure 3. Portofino Promontory (Genoa) shelf and slope Sparker 6 kJ seismic line. It is possible to see the notable continental slope sediments, following the continuous erosion caused by the deep and turbidity currents moving along the Canyon del Levante, parallel to the coastline.

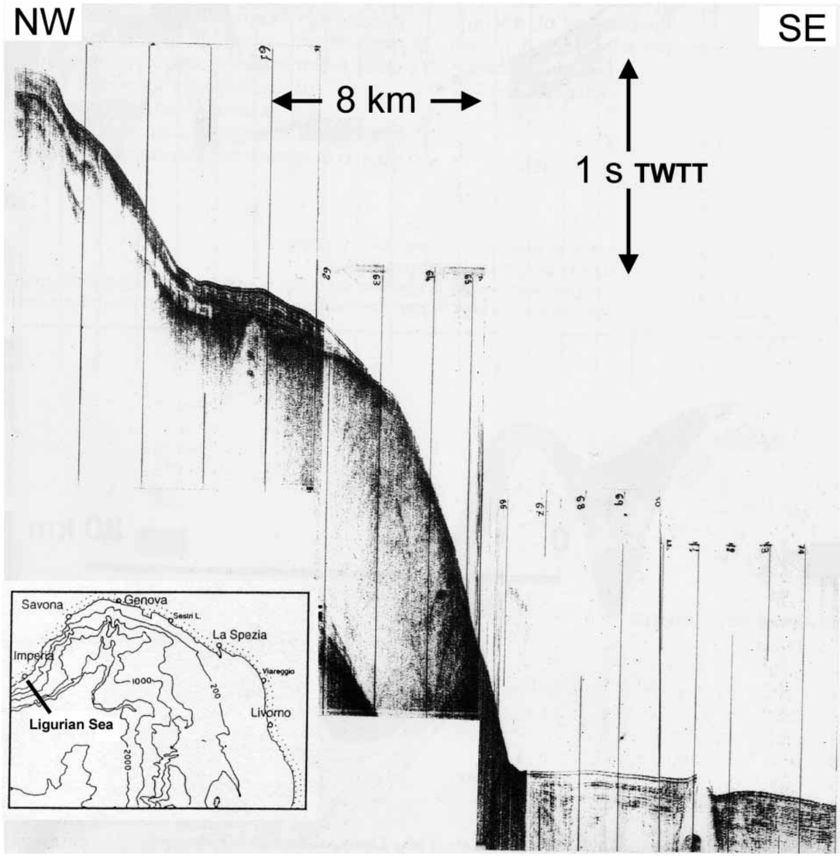

Figure 4. Imperia continental slope Sparker 6 kJ seismic line. Gravitative processes are evident along the steep slope and in deposits of the Continental Rise.

Canyon. This canyon shows unusual characteristics, and analysis has revealed its complex origin as the result of the interaction of a number of processes in a number of phases.

2. Hydrological changes and their effects

The Ligurian Sea is one of the most dynamic areas of the Mediterranean, representing the main 'source' of Mediterranean water and heat and it is, therefore, an essential component of the energy balance of the whole basin. The water and heat subtracted by the Ligurian Sea in winter are not returned during the rest of the year so that this basin plays a key role in the whole Mediterranean Sea. For example, the Ligurian Sea has a major impact on the formation of the cyclogenesis of the atmospheric field because $>$50% of the Mediterranean's low fronts originate here, sometimes with disastrous consequences (flooding) along the Ligurian and Tuscan coasts.

The formation of dense water in this area in winter determines the degree of oxygenation of the deep part of the western Mediterranean, in a way that is similar to that observed in the Adriatic Sea in the eastern Mediterranean.

The Ligurian Sea is dominated by a large and well-defined anticlockwise circulation fed by two distinct currents: the Tyrrhenian Current and the western Mediterranean Current. The first, typically flowing in winter, penetrates the Ligurian Sea through the Corse Channel with a yearly

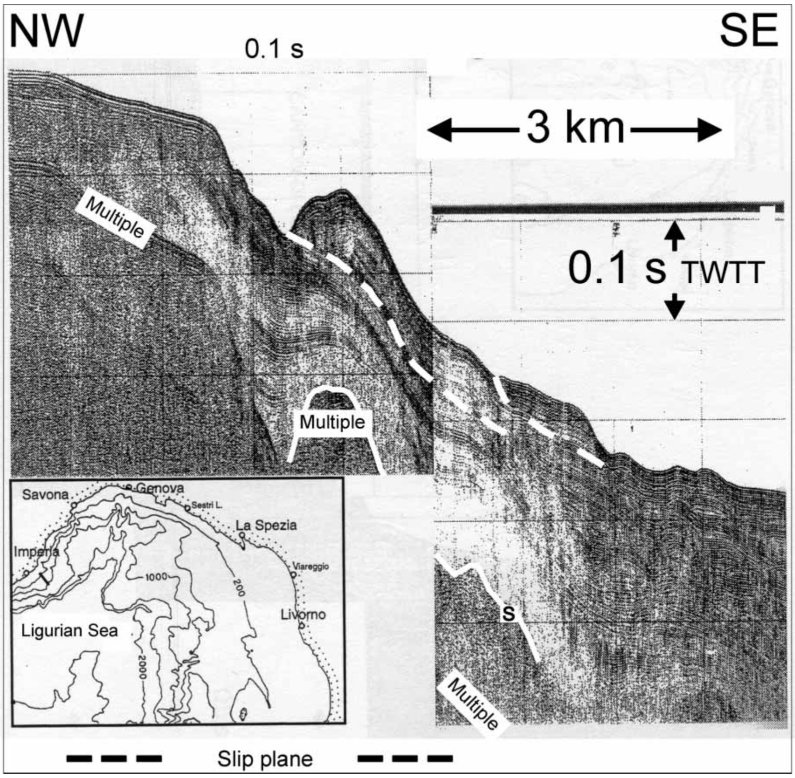

Figure 5. Est Imperia continental shelf Sparker 6 kJ seismic line. The seismic line shows an important gravitative event regarding the whole shelf break and other minor events along the continental slope.

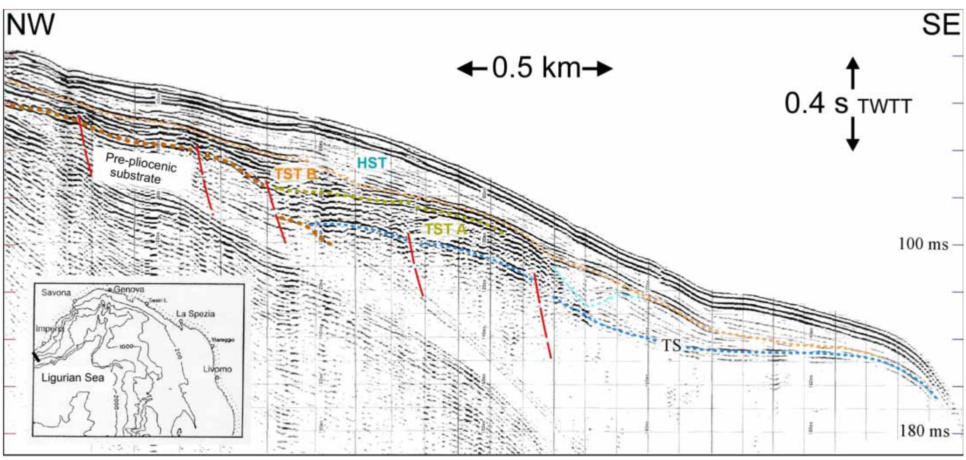

Figure 6. Riva Ligure (Imperia) Sparker 1 kJ high seismic line. The seismo-stratigraphy line shows the transgressive surface (TS) related to the sea level rise after the last minimum glacioeustatic event (18–20,000 years BP) and the transgressive deposits TSTA and TSTB related to old littoral bodies deposited during the stasis of the Versilian trangression (paleo-beaches). HST is the shelf recent sedimentary Holocene deposits.

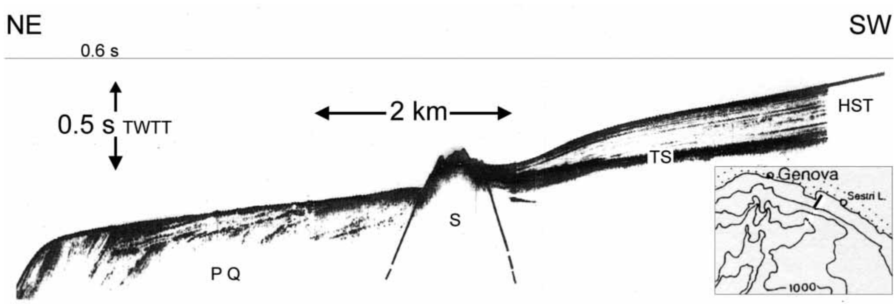

Figure 7. Portofino continental shelf (Genoa) Sub Bottom Profiler. It is possible to note the Versilian transgression surface (TS). In the eastern shelf this surface (TS) and the relict Versilian sedimentary bodies are covered by very thin Holocene sediments. S, substrate corresponding to the Punta di Portofino submerged outcrop; PQ, Plio-Quaternary sediments; HST, Holocene sediments.

average flux of 0.65 Sv [6], whereas the second, having a roughly double capacity, flows along the western coasts of the Corse Island.

In general, larger Tyrrhenian fluxes are observed in colder winters and vice versa. These differences in flux regime are linked to the North Atlantic Oscillation (NAO): particularly negative values of this index correspond to the highest water flux from the Tyrrhenian to the Ligurian Sea, whereas positive values of the index relate to the lowest flux.

Such trends may have deep and as yet not well-known effects on the reproductive biology and recruitment of many species, including fish of commercial interest. As an example, differences in the distribution and abundance of eggs and larvae of the anchovy (*Engraulis encrasicolus*) along Tuscanian and Ligurian coasts are related to the average spring–summer trend in the superficial current. In spring, higher densities of anchovy eggs are found in the Tuscany shallow shelf between Viareggio and La Spezia (which are reproductive areas for this species) compared with the deeper western coast, where in summer, higher densities of anchovy larvae are recorded, being transported westward by the coastal currents.

Recent studies have pointed out that interannual variations in the sea surface temperature can affect the abundance of the anchovies: in 1985, 1986 and 1993, characterised by high egg productivity, temperature trends were characterised by a fast increase (up to 4.1 °C) in sea surface temperature in May and by reduced temperature variability during the reproductive period (from June to August) [7]. By contrast, in 1991, characterised by a narrower spring temperature increase and by a high temperature increase in the following summer, the lowest abundances of anchovy eggs were reported. The recent increase in abundance of *Sardinella aurita*, a thermophilic, stenothermic and halophilic species, may be related to changes in the surface temperature of the Ligurian Sea coastal areas.

In winter, the Tyrrhenian current, supported by the north winds (tramontana), also regulates the coastal circulation: it moves the Ligurian anticlockwise gyre to the south-west. In recent decades, this process has sometimes occurred also in summer, favouring the coastal transport of southern warmer waters and causing the progressive deepening of the thermocline. Such an event might have induced the mass mortality events and the development of benthic mucilages [8–12] that have characterised the area in recent years. The same event has been claimed to be a concurring cause of the blooms of the toxic microalga *Ostreopsis ovata* occurred in the summer 2005, causing some sanitary problems [13]. In Liguria, *Ostreopsis* was firstly reported in 1998, between River Magra and the Gulf of La Spezia [14].

Also the abundance of *Vibrio* spp. is related to temperature, salinity, the concentration of organic matter and the presence of chitinous organisms (e.g. zooplankton), which are in turn controlled by larger scale climate variability [15]. Species potentially pathogenic to humans such as *V. cholerae*, *V. vulnificus* and *V. parahaemolyticus* have been observed in the Ligurian Sea with *V. parahaemolyticus* being the most frequent species: the occurrence and dominance of *Vibrio* spp. is, however, seasonal with a sharp increase at sea surface temperatures $>25\,^{\circ}$C (threshold temperature).

Increasing warming of the Ligurian Sea surface waters has been claimed as a major cause of the establishment of several populations of species with temperate and/or tropical affinity coming from the southern Tyrrhenian Sea [16], a process known as the meridionalisation of the Ligurian Sea (Table 1).

A theoretical study based on the analysis of pelagic larval transport [17] suggests that the connection between populations in the Ligurian Sea is lower than previously thought. In particular, the study pointed out that in summer, despite narrow temperature differences, low larval exchanges between the Ligurian and Tyrrhenian Seas can maintain the typical boreal affinity of the Ligurian populations. Yet, the connection between the two basins can be maintained through a series of stepping stones, such as alongshore constructions, wastes and floating detritus [18] or created after severe unpredictable extreme events, such as big storms or flux anomalies.

A comparative analysis of long-term data of the main physical–chemical variables (temperature, conductivity, dissolved oxygen, fluorescence, turbidity, wave height and direction), acquired using the ODAS-Italia1 buoy of CNR (43°47.36′N 09 °09.80′E), the SAMA-MAMBO buoy in the La Spezia area and the 'DYFAMED' buoy located 55 km from Nice, at a depth of 2300 m, revealed large fluctuations in dynamic and meteorological conditions for the offshore and in-shore areas at different spatial and temporal scales [19,20]. Similar large fluctuations have been reported for turbidity in the whole basin [21–23].

Among the most continuously investigated coastal areas of the Ligurian Sea, the Portofino Marine Protected Area (MPA) has been under investigation since 1999 [24–27]. The large data set available for this site, now included among the marine long-term ecological research (LTER)

Table 1. Exotic fish in the Ligurian Sea.

Name	Origin	When	Where	How many	Cause
Pomadasys stridens (Forsskål, 1875)	Indopacific	1968	Savona	1	Ballast waters
Sphyrna mokarran (Rüppel, 1837)	Circumtropical	1969	Camogli	1	Vagrant
Makaira indica (Cuvier, 1832)	Indo-Pacific	1986	Camogli	1	Vagrant
Sphoeroides pachygaster (Müller & Troschel, 1848)	Circumtropical	1986	Sanremo	12	Coloniser
Synagrops japonicus (Doderlein, 1884)	Indo-Pacific	1987	Portofino	1	Ballast waters
Pinguipes brasilianus (Cuvier & Valenciennes, 1829)	South Atlantic	1990	Loano	1	Ballast waters
Beryx splendens (Lowe, 1934)	Atlantic	1993	Portofino	3	Coloniser
Abudefduf vaigiensis (Quoy & Gaimard, 1825)	Indo-Pacific	1998	Riva Trigoso	1	Ballast waters
Pisodonophis semicinctus (Richardson, 1848)	Atlantic	1998	Leghorn	1	Coloniser
Carcharhinus falciformis (Müller & Henle, 1839)	Circumtropical	2001	Sanremo	1	Vagrant
Fistularia commersonii (Ruppel, 1835)	Indo-Pacific	2007	Sanremo	5–10	Coloniser
Lutjanus jocu (Bloch & Schneider, 1801)	Atlantic	2005	Varazze	1	Associated with floating objects

Note: Modifed from Orsi Relini [114].

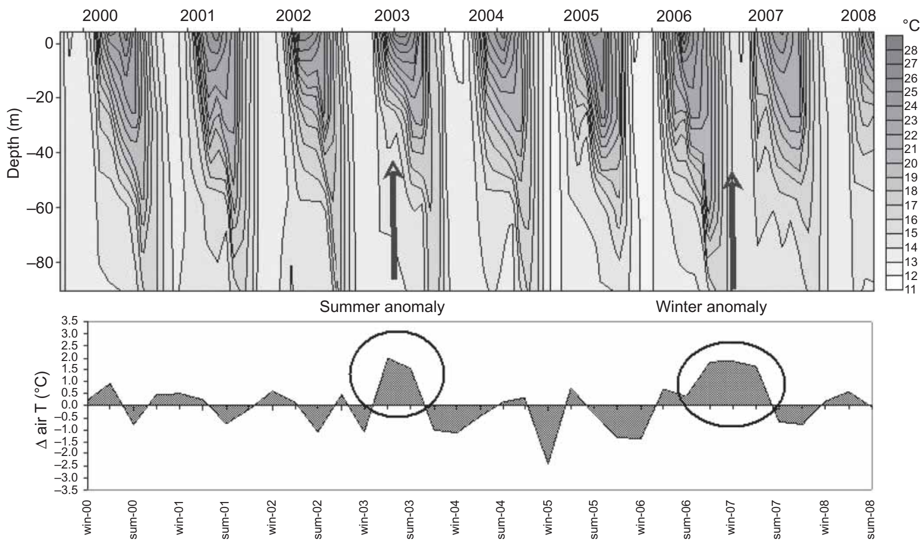

Figure 8. Significant water column and air temperature anomalies from 2000 to 2008 in the Portofino area.

sites, revealed, among others, the following phenomena: (1) an increase in the average monthly temperature along the water column in the last 10 years compared with the previous decade (1985–1995); (2) the episodic occurrence of significant thermal anomalies in summer 2003 and autumn–winter 2006/07 (Figure 8); and (3) the strong linkage between water temperature and the occurrence of blooms of the toxic dinoflagellate *Ostreopsis ovata*.

The accessibility of the Portofino MPA recently allowed its use as a preferential theatre for testing innovative devices for integrated coastal zone management, in particular, assessing new technologies for *in situ* and remote data collection [28–32].

For example, in the Portofino MPA there is currently a module of the integrated system WebGIS Marine Coastal Information System (MACISTE) developed to manage environmental information about coastal marine areas and particularly relevant and efficient for the multidisciplinary use of the data, reports and cartography.

3. The pelagic system

The strong counterclockwise circulation at the centre of the Ligurian Sea causes the upwelling of deep waters that supports a spring primary production, higher than the average for the western Mediterranean, with mesotrophic conditions in March–May and oligotrophic conditions in the summer and winter months. These features trigger the growth of large phyto- and zooplankton assemblages, patchily distributed in space and time, for which we have only scattered information.

Large seasonal blooms of jellyfish (mainly *Pelagia noctiluca*) and pelagic hydrozoans (*Velella velella*) represent a key step in the pelagic food webs, whose role is not yet well known, but must be relevant as the gelatinous plankton preys upon eggs and larvae of high-value commercial species and it is, in turn, preyed upon by some fish. In 2003, an unusual bloom of *Aurelia aurita* was recorded in La Spezia harbour.

The significant primary production relates to the development of primary consumers, such as the euphausid *Meganyctiphanes norvegica* [33] which plays a key role in all of the trophic webs that include the large pelagic organisms such as *Balaenoptera physalus*, a flag species of the pelagic system, that also reproduces in the Ligurian Sea [34].

The presence of cetaceans and other large pelagic predators in the Ligurian Sea suggests that this relatively small basin is characterised by high ecosystem complexity, which is also linked to the peculiar oceanographic dynamics and sea bottom topography. Among the most recurrent species of marine mammals, *Stenella coeruleoalba*, *Ziphius cavirostris*, *Grampus griseus* and *Physeter catodon* are often observed close to submarine canyons and seamounts. *Tursiops truncatus* is more common along the coastal areas characterised by a large continental shelf.

In order to preserve such an exceptional abundance of marine mammals for the Mediterranean, an International Whale Sanctuary was established in the Ligurian Sea, a protected area of 87,500 km^2 where extensive studies have been performed on the trophic web of the large pelagic organisms. The lack of a signed regulation makes the scientific management of this area particularly difficult because of the contrasting needs of the large commercial naval traffic and the protection issues.

Little information is available regarding the submarine canyons in front of Genoa, except for studies on particulate matter and upwelling [4,21] and on the transport of Fe and Cu [35]. In addition, the offshore seamounts (Banco di Santa Lucia, Banco di Ulisse), characterised by steep slopes, some of which host the white coral community, have been investigated little to date.

Similarly, little is known about the structure and dynamics of the bathyal communities, except for macrofauna and fish that show evidence of being depleted or modified, because of a clear decrease in filter- and deposit-feeders and an increase in opportunistic carnivores (scavengers) [36]. These areas are indeed subjected to intense trawling fishery activities that, together with increasing water turbidity and the general trophic conditions, are among the main causes responsible for the large ecosystem changes that have affected the white coral community in the Gulf of Tigullio.

The trawling fishery has caused not only structural changes in deep-sea benthic communities, but also the rarefying of the large populations of the crinoid *Leptometra phalangium*, which was abundant (15–16 per m^2) at the continental slope break until the 1930s, just before the Ligurian fishery began operating at these depths. Similar rarefaction has been experienced also by the gorgonians *Funiculina quadrangularis* and *Isidella elongata*, constituting different facies of the bathyal communities [37].

4. Threats to the Ligurian coastline

A high level of urbanisation characterises the whole Ligurian coastline, except for small portions (Capo Mortola, Portofino, Cinque Terre, San Rossore and a large portion of the Tuscany coast, South of Leghorn). Almost two thirds of the littoral are constituted by cliffs and promontories among which pocket beaches of different sizes are found mainly along the eastern side. They are fed by the debris produced by the instability of the high rocky coast and by the coarse pebbly–gravelly sediments of the small streams. An exception are the interdeltaic beaches of the Roja, Centa, Entella and Magra rivers and of some portions of the Savona coastline. These beaches, often small, are located at the mouth of main rivers and represent the sea front of small coastal plains.

Only 21% of the Ligurian coastline shows stable conditions. Analysis of the evolutive trends of the beaches, thanks to aerial photographs taken from 1944 and 2003, available at Regione Liguria, shows that 33% of the Ligurian beaches are under erosion, 49% are stable and only 18% are under accretion. Such stability is mainly due to the high level of protection of the beaches and to replenishment activities. In fact, to protect coastal urbanised areas, rigid structures (attached and parallel breakwaters, artificial islands, groynes, breakwaters and submerged barriers) characterise a large part of the littoral area and many beaches are replenished on a seasonal basis.

The net along-shore transport of sediments that constitute the emerged beaches and the submerged soft sediments is mainly directed towards the north-east on the west coast, and towards the south-east on the east coast; the main apport is represented by coarse sediments.

Along the east coast, the locally eutrophic waters are strongly influenced by the Tyrrhenian Current, characterised by low salinity and high nutrient content, enforced by the Magra River outflows. The Tuscany littoral area is mainly affected by the Arno River, whose effects are detected up to the Cinque Terre area [38]. All of this causes a high turbidity level of the coastal waters, that may cause a homogenisation of littoral benthic communities, with loss of sensitive sessile species.

On a regional scale, the main causes of regression of the coastal benthic communities and, in particular of meadows of the seagrasses *Posidonia oceanica* [39] and *Cymodocea nodosa* [40], are the building of the littoral railway line and consequent disposal of the debris at sea, urbanisation, harbour activities, rivers and coastal roads; other local impacts cumulate with the former and are little quantifiable, such as seasonal replenishments. Some studies have also evaluated the impact of boat anchoring on *Posidonia* meadows [41,42].

The Ligurian Sea hosts large harbour areas (Savona-Vado, Genoa, La Spezia, Leghorn) of high Mediterranean significance: in 2007, a total of 7880 ships passed through Genoa harbour alone. In addition, ∼20,000 berths are distributed in 84 marinas. It is evident that harbour activities and yachting had a significant impact on environmental conditions along the coast (distribution and structure of communities, organic enrichment, hydrocarbon pollution, acoustic pollution due to nautical traffic, solid wastes, etc.). Polycyclic aromatic hydrocarbon (PAH) concentrations in the water column, seston and plankton have been assessed in the harbour area of Sestri Ponente, which is also affected by urban sewage, and sediments have been assessed in the Voltri harbour area [43] and in some marinas [44,45].

To promote the environmental management of marinas, an integrated management protocol has recently been developed, based on the application of chemical–biological indicator sets and on the calculation of whole-system metrics for sustainability analysis. The application of a suitable developed model led to the computation of two new indices (portuality risk and vulnerability), which enable a preliminary evaluation of the potential environmental risks of marinas [44,46]. Studies on the structure of soft-bottom benthic communities (bacteria and meiobenthos) have been performed in highly organically enriched areas in order to evaluate the adaptations of these communities to anoxia and disturbance. Functional (i.e. ecosystem fever) and structural (dominance of tolerant nematode genera) changes have been correlated with the increase in organic load in the sediments [45,47–51]. In general, the stress caused by a diffused chronic pollution alongshore favours imposex in *Hexaplex trunculus* [52].

The largest oil spill in the Mediterranean occurred in the Gulf of Genoa: the *VLCC Haven* sank on 11 April 1991 releasing tens of thousands of tons of oil into the sea. The ecotoxicological effects of the disaster are well known, whereas only little information is available regarding the consequences on benthic communities [53].

A phenomenon that has only recently attracted the attention of the scientific community is the intrusion of seawater into the aquiferous systems inland (salt wedge), mainly due to the overexploitation of these systems, considerably depresses the piezometric surface and causes draining of seawater.

Particular attention has recently been given to the dispersal of suspended matter due to dredging at sea and in harbour areas and its effects on the environmental quality of the coastal area. This has recently been investigated by applying the CARLIT index within the framework of the Water Framework Directive (2000/60/EC). Application of this index to the Ligurian coast has evidenced the influence of the main urbanised areas and of river outflows on the quality of the upper infralittoral communities (Figure 9) [25,26]. In addition, the rock pool copepod *Tigriopus fulvus* has recently been utilised as an ecotoxicological model for studying the impacts of chemicals in the coastal habitat [54].

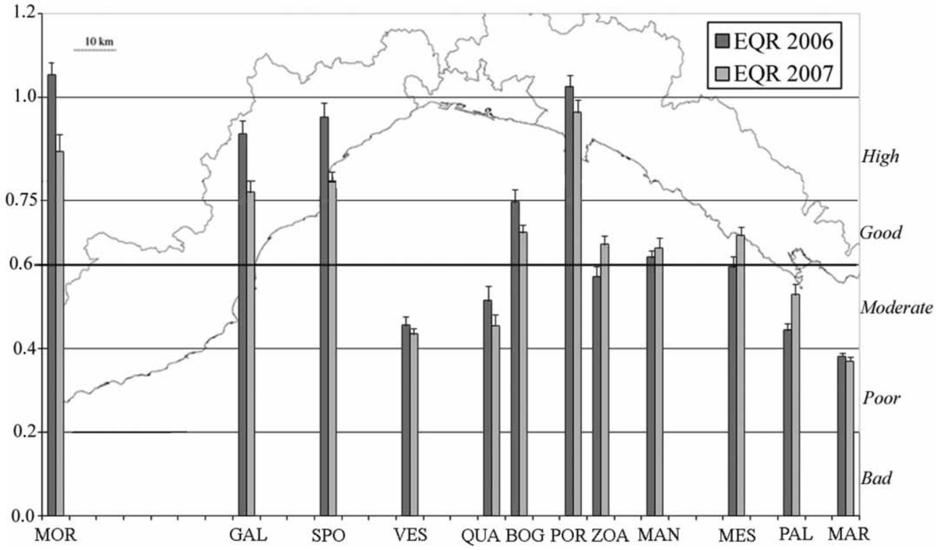

Figure 9. EQR values according to the CARLIT Index along the Ligurian coast in 2006 (dark grey) and 2007 (light grey). Reported values are the average at the stretch level (average of all individual measures of sectors along the whole stretch). Error bars: standard error. Modified from Asnaghi et al. [26].

The continuous use of sands from nearby areas to feed eroded beaches leads to the problem of the dynamics of transporting matter resuspended during dredging; this problem also concerns the transport of these sediments and disposal of the muddy layer that often covers sediments used for replenishment. The limits posed by dredging technologies (collection within a depth of 80 m) make this problem even more relevant, because *Posidonia oceanica* meadows, endemic of the Mediterranean Sea can be found at depths between 10 and 40 m; such depth proximity may be even more close than in spatial terms. One answer to this problem may be linked to the possibility of predicting the fate of suspended material using physical and/or mathematical models. On the west coast of the Ligurian Sea and in the Gulf of Tigullio, a lagrangian model has been applied to study the dispersal of contaminants [24]: these new models can perform objective analyses and define transport lines for suspended matter at a mesoscale level.

5. Biodiversity, endangered and alien species

Animal biodiversity in the Ligurian Sea is well known for Portofino, Calafuria (south of Leghorn) and part of the Tuscan Archipelago. Much less information is available for the Ligurian Sea marine macroflora.

For more than 150 years, many detailed faunal lists have been produced dealing with fish, sponges, cnidarians, molluscs, decapods and copepod crustaceans, echinoderms and other hard-bottom invertebrates (see http://www.sibm.it/checklist/ principalechecklistfauna.htm).

Studies performed in recent years, although not continuative, have provided much information about the structure and seasonal variations in the mesozooplanktonic assemblages, paying particular attention to some copepod species (*Centropages typicus*) [31,55,56] in relation to the prokaryotic biomass [57] and water quality [58,59].

To date, total marine biodiversity in the Ligurian Sea is detailed for only a few scattered sites such as the Portofino Promontory and the Gulf of Levanto: yet, these knowledge hotspots provide us with a certain picture of the biological variety. As an example, between a depth of 0 and 10 m, 92 species of sponges are known for the shelf coralligenous community of Bogliasco, compared with 74 species of sponges for Portofino. At both sites, these species represent $>10\%$ of the species richness of sponges for the whole Mediterranean Sea. These findings are indicative of our poor knowledge and possibly underestimate the biodiversity of the Ligurian Sea, and also the potential of this sea to represent a hotspot of biodiversity. Such poor knowledge is also the result of a lack of new taxonomic expertise, which is leading to the virtual disappearance of many animal taxa from the Ligurian Sea.

The distribution of littoral benthic communities is well known because the Ligurian benthic communities have been completely mapped at a scale of 1 : 10,000 [60]. Particular attention was given to the distribution and consistence of meadows of the seagrasses *Posidonia oceanica* and *Cymodocea nodosa* [61] because they may be considered indicators of the sedimentological balance of the submerged beaches.

The availability of historical maps of the Gulf of Tigullio has provided a first example of diachronic cartographic analysis for the Italian seas, as a tool to assess environmental changes and support the management of the coastal zone [40]. Similarly, in Liguria (Bergeggi and Portovenere), the first attempts to provide a thematic cartography for the management of the coastal marine 'territory' were performed [62].

The structure and dynamics of rocky benthic communities have been investigated particularly in the Portofino area, which still represents a biodiversity hotspot in the Ligurian seascape.

The littoral rocky bottoms, at depths below 25 m, are characterised by the coralligenous community, where studies have been performed on the population structure and dynamics of some filter-feeding species (*Leptopsammia pruvoti*, gorgonians and the red coral, in particular) in Portofino, Cinque Terre, Tino island, Calafuria, Elba and Capraia islands [10,63–67].

The carbonatic production of the coralligenous habitat and others characterised by a high degree of calcimass has been investigated [68–70]. These studies have highlighted that production of the coralligenous habitat is similar to the typical range encountered in tropical coral reefs. Studies on the growth rates and mineralogical features of carbonatic organisms of the rocky communities in La Spezia stressed the relationship between thermal variability in the water column and the calcium carbonate deposition of skeletal structures [71–73].

With regards to submarine caves, a habitat recently recognised by the EU as particularly endangered and deserving protection, data are available for communities in the Bergeggi and Tinetto caves [74], although little information is available for other Ligurian submarine caves.

Only scattered data are available for shallow soft-bottom communities. Some information is available for beach communities [75,76], the well-sorted fine-sand community, mainly in terms of the population structure and dynamics of the bivalve *Spisula subtruncata* [77], for the macrobenthic communities of the sands in *Posidonia* meadows [78] and for macro- and microcommunities of coastal sands and river mouths [79–82].

Little information is available on the so-called 'twilight zone' which is particularly affected by trawling and hosts charismatic species, such as the red coral *Corallium rubrum*, the antipatharian *Antipathella subpinnata*, the parasitic zoanthid *Gerardia savaglia* and the hydrozoan *Lytocarpia myriophyllum* that characterise the detritic bottoms at the base of cliffs. In particular, the four above-mentioned species are considered rare or threatened and have consequently been placed in Annex II ASPIM (Barcelona Convention) and in Appendix II of the Bern Convention.

Recent studies suggest that rocky benthic community structures in the Ligurian Sea are affected not only by water quality and exposure, but also by the mineralogical features of the substrate that, along the Ligurian coastline, show a mosaic distribution of ophiolites and serpentine rocks, mesozoic carbonate, Permo-Carboniferous basement and Meso-Cenozoic flysh, with high quartz content [83]. The quali-quantitative structure of benthic communities living on these different rocky habitats may be affected by the presence of quartz [84,85], although it is difficult to discriminate between a direct effect of the mineral and the roughness of the rocks. By contrast, the mineralogical features of the sediments do not seem to play a significant role in substrate choice for the polychaete *Sabellaria alveolata* when building its bioconstructions, whereas grain size of the surrounding bottom plays a major role.

The comprehension of cause–effect relationships between environmental changes and biodiversity shifts is limited to a small number of study areas [86]. Rocky benthic communities (rockpools, infralittoral fringe, upper infralittoral) have also been used in manipulative studies, mainly along the shores south of Leghorn, in order to understand mechanisms affecting their distribution, abundance and biodiversity [87,88]. The results obtained so far have highlighted the role of benthic interactions, mechanical disturbance (e.g. storms) and sedimentation in determining community structure and its variations at different spatial and temporal scales.

The lack of experimental data on large spatial and temporal scales represents a large gap in our knowledge, drastically limiting our capacity to foresee the consequences of growing anthropogenic impact and climate change on the biodiversity of the Ligurian Sea.

Among human activities, the date mussel fishery [89,90] has played a role in affecting the structure of calcareous rocky communities in some areas of the Ligurian Sea coastline (e.g. La Spezia), favouring a shift of photophilic benthic communities to a barren ground state, but this activity is now banned and the effects seem to have been much reduced.

The temperature anomalies of superficial waters recorded in the last 10 years have caused structural changes in fish, plankton and benthic communities. Long-term data collections, started in the 1980s, show changes in terms of both species composition and abundance in the rocky benthic communities of the Portofino area, particularly because of the thermal anomalies of autumn 1999 and 2003, when in the whole Ligurian basin large mass mortalities and mucilage proliferations occurred [8,11,12,91]. In the proximity of La Spezia, mortality events have seriously affected populations of *Cladocora caespitosa* [92] and of >80% of *Paramuricea clavata* colonies, favouring the spread of encrusting fast-growing species [11]. Other mass mortalities have been recorded south of Leghorn [93].

Contextually, starting from the late 1980s, thermophilous species have been first recorded: fish, invertebrates, macro- and microalgae that were not present in the past in the basin are now recorded. Among the fish recorded were: *Abudefduf vaigiensis*, *Beryx splendens*, *Carcharhinus falciformis*, *Fistularia commersonii*, *Lutjanus jocu*, *Makaira indica*, *Pinguipes brasiliensis*, *Pomadasys stridens*, *Sphoeroides pachygaster*, *Sphyrna mokarran* and *Synagrops japonicus*, with only one species, *F. commersonii*, representing Lessepsian colonisers (Table 1).

Other species have only enlarged the northward boundary of their distribution: *Pomadasys incisus* [94], *Thalassoma pavo* [95], *Xyricthys novacula*, *Coryphaena hippurus*, *Sphyraena viridensis* and two cryptobenthic species, *Parablennius pilicornis* and *Scartella cristata* [96,97]. Some species were previously reported sporadically in the Ligurian Sea in the nineteeth century (e.g. *Thalassoma pavo*), suggesting that climatically favourable periods occurred in the Ligurian area also in the past.

However, fish assemblages have shown large changes in the last 10 years: in addition to the establishment of thermophilic populations (e.g. *Coryphaena hippurus*, *Sphyraena viridensis*), carangids (*Seriola dumerili*) have generally increased in numbers, although some small-sized tuna species (e.g. *Auxis rochei*) and some large pelagic predators such as sharks have decreased. Among these, it is worth noting the decrease in species of economic interest, such as the dogfish (*Mustelus mustelus*, *M. asterias*). By contrast, a large increase in populations of the brown grouper (*Epinephelus marginatus*) has occurred in the Portofino MPA where, currently, some 100 specimens can be observed: this is probably the most spectacular effect of the Portofino MPA and the banning of spear fishing. Concurrently, in the Portofino area a large number of fish species are observed at scuba depths (77–94 m) [98].

From a 'global change' point of view, the spread of the green algae, *Caulerpa taxifolia* and *C. racemosa*, in the Ligurian Sea is particularly interesting [99]. Along the coast, these species were first sighted in Imperia in 1991: *Caulerpa taxifolia* spread most along the western coast, strongly modifying the structure of littoral communities. Fishermen are affected by the presence of this alga, but also contribute to its diffusion through their fishing gear, particularly trawlers and gill nets. *Caulerpa racemosa* is similarly invasive and has been reported in many areas of the Ligurian Sea, including the MPAs of Bergeggi, Cinque Terre and Portofino and Portovenere area, a regional protected site.

6. Biological resources

In the Ligurian Sea, professional fisheries operate both inshore (artisanal fishery) and offshore, trawling the continental slope, using gill nets and longlines on neritic and epibathyal grounds, and with drifting longlines also far from the coastline.

According to the 2008 statistics of the Italian Fishery Ministry, 558 fishing boats were operating in Liguria in 2006 (4% of the national fleet), catching a total of 4905 t (only 1.8% of the national catch): in fact, the boats are smaller and less powerful than the national average.

Yet, general statistical information on the Ligurian fleet and its catches are scant and cannot be used to plan any management of the resources. Good information on the catches is available (assessment of the demersal resources and of the captures in the main Ligurian harbours). For the large pelagics and trawling fishery good information on the catches is available, thanks to many research projects carried out mainly in the framework of the Italian law 41/82 [100].

In addition, the increased market demand for small pelagics, mainly the anchovy, has stressed fluctuations in the abundance of this species through fluctuations in its market price. Assessment of Ligurian stocks of this species must take into account the high degree of uncertainty in the estimates and complexity of the interactions among environmental factors, affecting temporal fluctuations in the biomass: in 1999–2001 the standing stock was estimated at between 1000 and 10,000 t, whereas in 2004–2007, it was $\sim$3600–7300 t. The shortness of the time series does not allow us to assess whether the apparent decrease in biomass is related to overfishing or to the natural biological cycle, possibly in relation to changes in environmental conditions.

A winter fish resource is the transparent goby (*Aphia minuta*) whose catches in the years 2004–2005 were monitored and the growth in captivity of its juveniles studied.

Among the 10 species of commercial interest on a national scale, the deep water shrimp *Aristeus antennatus* (the giant red shrimp *Aristeomorpha foliacea* has virtually disappeared since the 1970s), the Norway lobster *Nephrops norvegicus*, the European hake *Merluccius merluccius*, the red mullet *Mullus barbatus*, the greater forkbeard *Phycis blennoides* and the curled octopus *Eledone cirrhosa* are quantitatively relevant in the Ligurian Sea. The latter two species have the largest importance, compared with any other Italian sea: in particular, fishery of curled octopus juveniles represents an ancient tradition and provides a high value commercial product.

In recent years, an increase in the occurrence of the deepwater pink shrimp *Parapenaeus longirostris* has been observed. Red shrimps started to appear in the Ligurian market in the 1930s and represent the most valuable fishery resource of the region, followed by the small pelagics and gadiforms, in particular, the European hake. The large pelagics are also relevant, particularly along the western coast.

The inshore fishery, although a highly specific artisanal activity, suffers from general ageing among the fishermen (the average age of artisanal fisherman in Liguria is 57 ± 15 years) and from competition with other activities, such as yachting and other uses of the coastal area. A single datum synthesises the critical nature of the artisanal fishery: only 11% of Ligurian fishermen has a son who is a fisherman: within 20 years, it will be difficult in Liguria to find a fisherman who can teach new generations.

In the debate on the management of demersal resources, we need to take into account the particular features of the Ligurian fishing grounds, which have very few shallow areas and push fishery activities to deeper waters; similarly, we need to consider the artisanal character of the fishery with small numbers of both boats and people.

A general concern is about the protection of the juveniles through appropriate choice of times and areas where to set up specific regulations for the human activities [101], and where trawling is forbidden in order to save the nurseries of currently overexploited species. In addition, protection of the largest individuals should be assured, because they are usually large reproductive females that presumably find refuge at greater depths.

Also, for the red shrimps it is necessary to take a precautionary approach on the basis of their slower growth and greater longevity than was previously thought [102]. A life span of up to 10 years has been estimated for the genus *Aristeus*. Yet, much remains unknown about the life cycle of this species: we do not yet know where the larvae are found and, eventually, where recruits come from. Consequently, much remains to be done to obtain a larger valorisation of the resource and, most of all, for its protection.

Also worth noting is the impact of fishing devices (trammel-nets, vertical and bottom longlines) on the hard bottom benthic community structure [103]: the damage caused by fishing gears on slow-growing erect sessile species (mainly gorgonians, red coral and bryozoans) represents a real biological threat that triggers necrosis of the tissues and the growth of epibionts that can cause the death of the colonies.

Finally, amateur fishing has to be considered; in Liguria this is not quantified (certainly playing a significant effect), often leading to strong conflict with professional fishermen.

The increasing market demand for products from the sea is driving the development of some aquaculture in the Ligurian Sea. Mussel aquaculture started in La Spezia in 1887: at present, with 96,000 m^2 implants, it produces 34,000 $q \cdot year^{-1}$ (8.3% of the national production) at a total value of 4.5 million euros. At the beginning of 2005, some small experimental oyster aquaculture implants were set up in La Spezia Gulf, and the results are encouraging, particularly in terms of the quality of the product.

Ligurian fish aquaculture is performed completely offshore, in front of Alassio, Lavagna and La Spezia. The total production (mainly sea-bass, gilthead seabream and, secondarily, seabream and meagre) is around 800 $t \cdot year^{-1}$ (4% of the national production), corresponding to an income of $\sim$6 million euros.

The environmental and sustainability analyses of aquaculture implants show that their impact decreases with the distance from the coast [104]. The analyses were performed by studying alterations in the biochemical composition of the organic matter and the structure of bacterial and macrobenthic communities. A recent study set up the POM-LAMP3D model which allows evaluation of the spread of pollutants derived from aquaculture and their persistence in the environment, by simulating the degradative processes (module FOAM) [105]. The study was addressed to identify a sustainability indicator for the rearing process, was particularly innovative, and was coupled with emergy and network analyses.

In Liguria, the study of artificial reefs has a long tradition: their main use here is to impede trawling activities in forbidden areas, but they also contribute to an increase in the fish and invertebrate biomass [106,107].

7. The environmental policy

As part of its environmental policy, the Ligurian Sea is host to a number of MPAs of high relevance: Portofino, Cinque Terre and Bergeggi, in addition to the forthcoming Gallinara and part of the Arcipelago Toscano National Park.

Portofino MPA achieved the Specially Protected Area of Mediterranean Interest (SPAMI) title from the Regional Action Centre – Specially Protected Area (RAC-SPA) of Tunisi in 2005 and, since 2007 has been one of the LTER sites, a national web where it is possible to test trends in the main environmental variables in Italy, thanks to long-term data collections.

In addition, the Regione Liguria has given some regional protection to marine areas, creating regional protected areas: Portovenere and Capo Mortola, and designating 26 Sites of Communitarian Interest (SIC). These SICs are mainly concerned with the conservation of meadows of the seagrass *Posidonia oceanica*, whereas the Whale Sanctuary, included in the SPAMI list in 2001, aims to preserve the offshore habitat.

In addition, the few estuaries present along the coast have been protected, although they are often endangered by the portuality. The Ligurian estuaries are in fact included in the list of SICs and the Magra estuary, is also in a Regional Natural Park, as are the Tuscan ones [78,81].

In addition to the legal protection, it is necessary to ensure a real control of the application of the protection itself [108,109] and concrete management of activities that can affect the coastal area. The need for correct management of the coast goes far beyond the protection of punctual valuable sites. In this framework, research projects have been developed to evaluate the sustainability level of the coastal areas through the application of indicators from the WG-ID working group of the European Community and the definition of new system indicators. Integrated methodologies of co-management, involving regional and local authorities, have been set up in order to define strategies at the regional scale for ICZM [110].

Given the role played by tourism in Liguria, in terms of both economical resources and environmental stress, attention has been focused on the beaches. Ecological quality evaluation of the 'beach ecosystem' has been performed [111,112], defining an integrated management model [110,113]. Furthermore, criteria for application of the Ecolabel to recreational beach activities have been developed and their ecological footprint has been assessed in order to increase the sustainability of these activities.

Attention has also been given to the study of the scuba tourism, mainly in relation to its amelioration in the framework of MPAs.

8. Concluding remarks

The main highlights of our review of the scientific knowledge available for the Ligurian Sea can be summarised as:

1. Good knowledge of the geological and structural evolution of the Ligurian–northern Tyrrhenian basin, as well as of the sedimentation dynamics of the littoral and deep bottoms, with particular attention to the sedimentation balance of the beaches and their erosive processes.
2. Very good comprehension of the seasonal and interannual dynamics of water masses. We pinpointed that hydrodynamic, geomorphological and meteo-oceanographic conditions provide the coastal area of this basin with a continuous exchange of coastal water masses that can mitigate potential alterations due to human activities. We stress that this information is particularly important in order to evaluate direct and indirect effects of climate change on populations and communities in the northern basin of the western Mediterranean.
3. Good knowledge of the distribution of coastal communities which is a prerequisite for the design of new studies aimed at conservation of the coastal zone within the framework of its integrated management.
4. An urgent need to enlarge the current knowledge to the whole continental shelf of the Ligurian Sea and to the submarine canyons and rocky bathyal bottoms, including the offshore seamounts.

5. Evident suffering in several economic sectors associated with the management and exploitation of biological resources allocated in the coastal area, because of incomplete tools and applications.

Furthermore, our analysis pinpoints the need for long-term studies and further investigation of those areas that have been little investigated to date. We stress here that only properly addressed studies, profiting more proper experimental approaches and sampling designs across appropriate spatial and temporal scales might allow better comprehension of the functioning of the Ligurian Sea ecosystems, to evaluate their health conditions and understand the dynamics of the main variables that affect the distribution of single species and communities (including species of high economic value).

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