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SUSTAINABLE MANAGEMENT OF THE MEDITERRANEAN

The future of the Mediterranean Sea Ecosystem: towards a different tomorrow

Ferdinando Boero

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Abstract The structure and function of the Mediterranean Sea Ecosystems (MSE) are rapidly changing. Global warming is the main driver of change, and the MSE responses are dramatic. The establishment of non-indigenous species, heavily influenced ecosystem functioning; human pressures such as overfishing, triggered regime shifts such as that from fish to jellyfish; the Eastern Mediterranean Transient changed the circulation patterns of the Eastern Mediterranean basin. Models did not predict these changes. Science, so far, focused much on the constraints that lead to regular sequences of events, allowing for predictions. In periods of rapid change, though, the historical nature of ecology becomes prominent, and contingencies acquire an overwhelming importance. This calls for new approaches to the study of complex systems, for instance with a shift from monitoring to observation, with a revival of natural history. The identification of cells of ecosystem functioning, based on oceanographic processes that enhance production at different levels of marine food webs in specific areas, is a challenge for future studies that will eventually lead to better management and protection of the marine natural heritage. Even if historical systems do not allow for predictions, some trends are clear and a set of possible scenarios of what will happen in the future Mediterranean Sea can be proposed.

Keywords Mediterranean sea · Climate change · Biodiversity · Ecosystem functioning

1 Introduction

The Mediterranean Sea, a miniaturized ocean that responds quickly to climate change, is a proxy to understand global phenomena. The richness of its biota has no counterpart in other European seas, adding value to the use of this basin as a mega laboratory where to assemble various scales of knowledge so as to acquire holistic understanding about the emerging properties of complex marine systems. Mediterranean Sea Ecosystems (MSE) went through a complex geological and bio-ecological history that was greatly affected by human presence since ancient times (Bianchi and Morri 2000). Only recently, however, due to the power of their impacts on the environment, humans are exerting unprecedented pressures on MSE. The Suez Canal linked the Red Sea with the Eastern Mediterranean, triggering biogeographic changes comparable to those generated by continental drift: with the Lessepsian immigration, hundreds of Indo-Pacific species established into the MSE, favored by global warming (Lejeusne et al. 2010). Furthermore, shipping and aquaculture greatly changed the MSE: the establishment of *Caulerpa* species in the Mediterranean, and that of the ctenophores *Mnemiopsis* and *Beroe* in the Black Sea are paradigmatic under this respect. The Eastern Mediterranean Transient (EMT) changed both the physics and the biology of the Mediterranean Basin (Danovaro et al. 2001). These large-scale changes are in synergy with local impacts, such as coastal development,

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increasingly efficient fishing gears, and mariculture expansion. Each impact is conducive to change, but it is difficult to predict the outcome of synergistic multiple stressors (Claudet and Fraschetti 2010).

After assessments of the state of MSE (e.g. Coll et al. 2010; Bazairi et al. 2010) in this period of rapid change, it would be very useful to attempt predicting their possible future states, so as to be ready to face novel conditions.

2 Predicting the behavior of historical systems

Scientific disciplines can be either historical or ahistorical (Cleland 2002). Ahistorical disciplines study phenomena obeying rigid laws that, once identified, allow predicting the future, whereas historical disciplines (like ecology and evolutionary biology), albeit constrained by the laws of ahistorical disciplines, study phenomena that are inherently unpredictable due to their high sensitivity to contingencies (Boero et al. 2004, 2009). The timing of sunrise and sunset and seasonal changes in day length, for instance, are ahistorical and predictable, whereas the weather is historical and inherently unpredictable over the medium-long term, while being nonetheless regulated by solar energy. It is epistemologically wrong to attempt to understand historical systems using the tools of ahistorical ones. Reductionism requires disassembling a difficult question into a suite of easy questions that, once answered, lead to the illusion of having answered the difficult question. In this framework, Boero (1994) distinguished fluctuations, i.e. the regular alternation of different phases through year and multiyear cycles, from variations, i.e. changes in the regularity of phenomena. Furthermore, Boero (1996) and Boero et al. (2008a) stressed the importance of episodic events (i.e. contingencies and/or irregularities) in changing the regular functioning of biological systems.

Ecology, a historical discipline, requires scientists to act as historians. Charles Darwin defined himself a "naturalist" and his discipline was Natural History: the tools of natural history can be very powerful, even if they do not pretend to predict the future. The attempt to transform ecology and evolution into "predictive sciences" describing nature with algorithms led to dismiss Natural History. Eminent scientists (e.g. Ricklefs 2012; Tewksbury et al. 2014) denounced this mistake, stemming from the evident failure of ahistorical approaches to solve historical problems. Historians do not predict the future; they describe the patterns of history and infer about the processes that determined them, acquiring insight that might be used to depict future scenarios. Economy, just like ecology, is a historical discipline and is very sensitive to contingencies while, however, obeying the basic laws of nature. Many economists, for instance, preach the continuous growth of human economy, but if something grows (e.g. the economic capital), then something else degrows (e.g. the natural capital) (Pignatti and Trezza 2000; Boero 2012): we can predict that our growth will eventually stop (all growths are finite, it is a law of Nature), but not when and how.

The identification of the drivers of past, recent, and present change provides insights on the processes that led to the observed patterns, allowing depicting possible future scenarios. In this framework, natural history is the only discipline that allows describing the structure of ecological systems and to infer about the processes that determine their function. Physical conditions constrain bio-ecology, but their knowledge is not sufficient to understand it. Temperature increases, for instance, lead to the establishment of tropical species in MSE; the new conditions explain the observed biotic change that, indeed, would not occur if temperature was decreasing instead, but physics cannot predict the species that will arrive, the rate of invasion and the impacts on MSE.

3 Great changes are taking place

In the last decades, the MSE went through a series of changes that altered their features in a dramatic way and that have been studied in isolation from each other, with lack of appreciation of their synergies.

3.1 Adriatic phase shifts

The Adriatic Sea, due to the great nutrient inputs from the Po River, has been for centuries among the most productive basins of the whole Mediterranean Sea. In the early eighties, however, the outbreaks of the jellyfish *Pelagia noctiluca* reduced fisheries' yields, clogging nets and eating all fish eggs and larvae, and also the crustacean food of larvae and juveniles, so impairing fish recruitment, as the ctenophore *Mnemiopsis* did in the Black Sea (CIESM 2001).

When the *Pelagia* years came to an end, dinoflagellates replaced jellyfish, flagellating the whole northern and central part of the Adriatic, with intense red tides along the Italian coast. The blame went on nutrients, whose inputs were contrasted with many actions. After a series of years characterized by red tides, mucilages due to intense bacterial metabolism replaced harmful algal blooms (Boero 2001; Boero and Bonsdorff 2007; Conversi et al. 2010). Apparently, these dystrophic events do not take place during thaliacean blooms since thaliaceans remove all microorganisms, preventing their proliferation. Either the herbivorous gelatinous zooplankton pathway (the Thaliacea) or the carnivorous zooplankton pathway (the jellyfish

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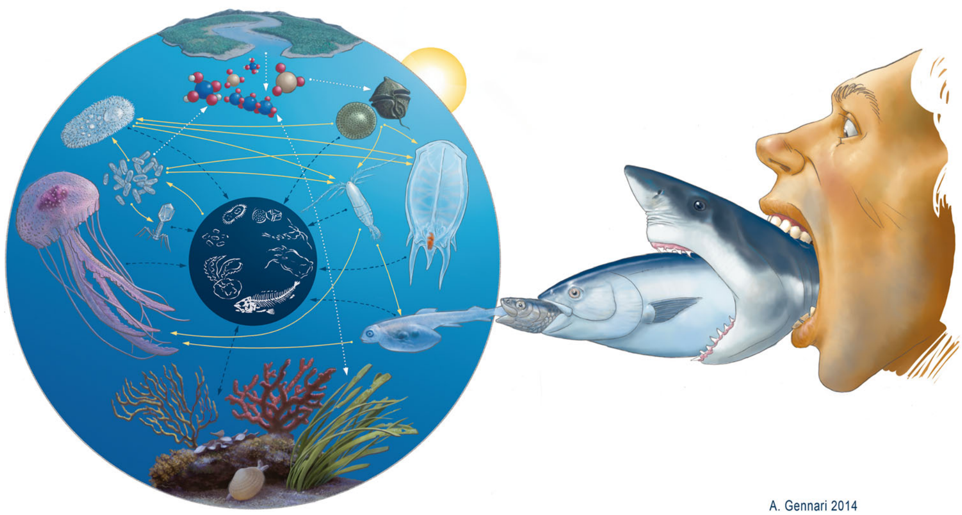

Fig. 1 Main marine trophic pathways. All organisms die (*central black circle*) and enter the microbial pathway, being decomposed by heterotrophic bacteria that, together with terrestrial runoffs, make nutrients available to phytoplankton production. Bacteria are killed by viruses and can be preyed upon, together with phytoplankton, by heterotrophic microbes such as flagellates. The microbial pathway fuels the crustacean-fish pathway that humans widely use. The gelatinous pathway can be herbivorous (dominated by thaliaceans, tapping from the microbial pathway) or carnivorous (dominated by either cnidarians or ctenophores, tapping from the crustacean-fish pathway). Water column organisms are strictly connected with benthic ones. *Dotted arrows* biogeochemical fluxes. *Dashed arrows* particulate organic matter fluxes. *Solid arrows* trophic links. *Art* Alberto Gennari

and the ctenophores) can short-circuit the usual functioning of marine ecosystems, based on a microbial pathway that sustains the crustacean-fish pathway, and the intra-ichthyic pathway we tap from (Fig. 1). Boero et al. (2008a) remarked that, due to their irregular appearance, gelatinous zooplankton blooms usually remain unstudied: we concentrate on regularities and disregard contingencies and irregularities.

After the fish–jellyfish–red tides–mucilages regime shifts, the Adriatic Sea is now much less productive than before, also because nutrient inputs are lower than in the past. Global change has influenced temperature and riverine regimes, with such deviations from norms as the EMT. The change in the functioning of Adriatic Sea ecosystems is due to an intricate suite of physical and biotic changes, and to human impact, from localized to global.

The periods of Adriatic history were studied in isolation from each other: only the proximate causes were considered, and the disregard of history prevented the identification of the ultimate causes of the regime shifts. Having identified correlations (e.g. nutrient availability correlated with great production) does not mean to have identified causation (the observed production might be due to other causes besides the nutrients): multiple causation is the rule in complex domains where the subtle intertwining of many drivers determines the course of events.

This does not mean that, if there are jellyfish blooms, then red tides will occur, followed by mucilages. This pattern of events, a clear case of trophic downgrading, took place in the Adriatic, but its occurrence is not a universal law, applicable to all situations. The trophic downgrading of Mediterranean ecosystems (Britten et al. 2014) evidenced by the Adriatic phase shifts is probably both a cause and a consequence of jellyfish prevalence.

3.2 From a fish to a jellyfish ocean

Jellyfish blooms are increasingly frequent throughout the world ocean (Boero et al. 2008a) with impact on fisheries, aquaculture, industry, and tourism (Boero 2013). Mills (2001) collated a series of localized reports into a general framework and evoked a global regime shift: from a fish to a jellyfish ocean. In spite of the great impacts, however, research on jellyfish blooms is scant, since the scientific community is not equipped to appreciate them.

To cope up with lack of large-scale efforts in the study of gelatinous plankton, a citizen science campaign is being conducted along the Italian coasts (8,500 km) since 2009 (Boero 2013). Thousands of records per year led to an unprecedented coverage of gelatinous plankton occurrence, with many new records, such as those of the alien ctenophore *Mnemiopsis leidyi*, the tropical scyphozoan *Phyllorhiza punctata* (Boero et al. 2009), the Atlantic scyphozoan *Catostylus tagi* (Boero 2011a), and the new scyphozoan jellyfish *Pelagia benovici* that Piraino et al. (2014) described from a population that suddenly became established in the gulf of Venice.

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The patterns of presence of indigenous species were also reconstructed. In spring–early summer, for instance, regular blooms of *Velella velella* were recorded from both the Ligurian and the Tyrrhenian Seas, with possible impacts on fish recruitment. The siphonophore *Physalia physalis* was recorded several times, with many cases of serious stings to humans. *Pelagia* was regularly abundant in the western basin, whereas it was almost absent from both the Adriatic and the Ionian seas (see Canepa et al. 2014). *Rhizostoma* was everywhere, with resident populations at selected places. The cubozoan *Carybdea* was recorded from the whole coast, mostly in correspondence with coastal defences. *Cotylorhiza* was recorded from the whole coast, starting from mid August, the blooms lasting until late September. Boero et al. (2013a) reported extensive thaliacean blooms. In the summer 2014 citizen scientists photographed the giant jellyfish *Drymonema dalmatinum*, a typical Adriatic species that was unrecorded since more than half a century.

No modeling led to predict the regime shift from fish to jellyfish, whose causes are probably manifold, from climate change to overfishing: an increasingly gelatinous future is ahead of us (Boero 2013).

3.3 Summer thermal stratification, mass mortalities, and phenology changes

Summer solar radiation warms up the sea surface and a warm layer becomes established, especially near the shore, reaching about 12–15 m depth in the Ligurian Sea and much deeper levels in the southern part of the basin. The abnormal deepening of the warm surface layer caused massive mortalities of organisms that do not tolerate high temperatures (Cerrano et al. 2000). The bearing of global warming on coastal waters' thermal stratification is almost uninvestigated; surface temperatures are monitored from satellites, but temperature distribution along the water column is not. The shallowest depth where species of cold-water affinity thrive might be a proxy to evaluate both the average depth of the warmer layer and the impact of global warming on marine communities, in case of mass mortalities.

In a study on the Hydrozoa of Portofino, Puce et al. (2009) compared the recent species composition and phenology with those of the early eighties (Boero and Fresi 1986). Winter species are now restricted to deeper levels and thrive for shorter periods than in the past, whereas summer species are present throughout the year and have increased their reproductive periods. After three decades, this fraction of biodiversity (hydroids) is showing much different features: the species of warm-water affinity are favored, those of cold-water affinity are in distress. What documented for hydroids is probably happening for many other groups, as a reaction of biodiversity to global warming.

3.4 Cold engines, the EMT, and extinct species

In the Mediterranean Sea, strong cold winds lead to deep-water formation due to a complex suite of events. The cold, saline and oxygenated surface waters of the Gulf of Lions and of the northern Adriatic Sea sink to the bottom of the western and eastern Mediterranean, respectively, vivifying their deep waters (Fig. 2). The North Aegean "cold engine" replaced the Northern Adriatic one during the EMT (that was not predicted by current oceanographic "predictive" models) with large impacts on both the physics and the biology of the whole basin (Danovaro et al. 2001; Boero et al. 2008b). An obvious impact of global warming on the Mediterranean Sea is a less pronounced temperature decrease in the coldest parts of the basin that might impair deep-water formation, as already happened with the EMT. As a worst possible scenario, if global warming will influence the "cold engines", and Mediterranean deep-water formation will be reduced, the basin might go through permanent stratification, with dramatic impacts on biodiversity. Many endemic species have been described from "cold engines" areas, including endemic families, such as the Paracorynidae and the Tricyclusidae (Hydrozoa). Higher temperatures in these cold areas determine new conditions that are less conducive to the thriving of cold-water species, and there is a possibility that some of them might become extinct (Boero et al. 2013b). A list of all the endemic species in these areas might become a list of putative extinct species that, if unrecorded after specific searches, might be considered at least endangered and included in red lists (Boero and Bonsdorff 2007; Boero 2011a).

3.5 Alien invasion and indigenous biodiversity

Global warming is leading MSE into a new state, with the establishment of large numbers of Non-Indigenous Species (NIS) of warm-water affinity (Zenetos et al. 2010). Tropical species enter through the Suez Canal (the Lessepsian immigration), or through either deliberate (e.g. the bivalve *Tapes philippinarum*) or accidental (e.g. the alga *Caulerpa taxifolia*) human transport. Shipping is also a mean of introduction (CIESM 2002): the ctenophore *Mnemiopsis* reached the Black Sea in ballast waters, causing an ecological and socio-economic catastrophe (CIESM 2001).

The detection of NIS requires world-scale taxonomic expertise, since NIS can come from any region. The most conspicuous species are easily identified, but it is highly probable that the contingent of NIS in MSE is much higher than currently perceived. A basin-wide assessment of the

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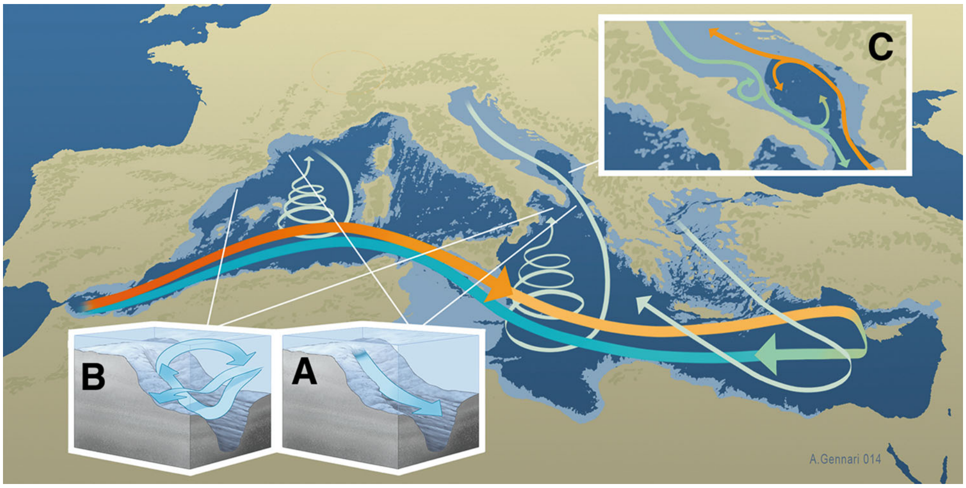

Fig. 2 Circulation patterns in the Mediterranean Sea, from the large to the small scale. The Gibraltar Current enters from the surface, reaches the Eastern Mediterranean and comes back, as Intermediate Levantine Current, flowing out from the deeper part of the Gibraltar Strait. The Cold Engines of the Gulf of Lion, the Northern Adriatic, and the Northern Aegean are sites of deep-water formation and renew the deep waters of the basin through a cascading that flows through canyons (**a**). The canyon system along the coast can also generate upwelling currents (**b**) that reinforce deep-water renewal, supplementing the cold engines. The coastline, as shown in the inset of the Otranto Strait (**c**), induces the formation of gyres and eddies. *Art* Alberto Gennari

whole biodiversity of the MSE at species level is particularly necessary, so as to make an inventory of our present natural capital, integrating the old species lists with the new records, and assessing the status of putative extinct species. Many groups have never received monographic treatment, and most monographs are obsolete, with just few exceptions (e.g. Bouillon et al. 2004): in the era of biodiversity, taxonomic expertise is rapidly vanishing (Boero 2010).

3.6 How many habitats?

The Habitats Directive of the European Union identifies Habitats as the best conservation units: protecting them, in fact, has a positive impact on the species that inhabit them, even unknown ones. Habitats mapping, with careful evaluation of their state and distribution, is a prerequisite to efficient measures of protection and management that, in their turn, require identification of threats to habitat health and the remedies to their degradation (Claudet and Fraschetti 2010). Currently recognized habitat types are based on attempts at scoring the “most important” species assemblages associated to a given habitat. Fraschetti et al. (2008) proposed to classify habitats according to their geological features, their level on the shore, and their living components arranged in a hierarchy envisaging bioconstructors (e.g. coralligenous formations and sea grass meadows) as the most important ones, followed by non-bioconstructor permanent habitat formers (e.g. gorgonians), then by seasonal non-bioconstructor habitat formers (e.g. algae of the genus *Cystoseira*), and so on. Fraschetti et al. (2013) showed that Marine Protected Areas enhance biodiversity stability through habitat conservation; a further step will be the establishment of networks of MPAs.

4 From the large to the small scale and back: the cells of ecosystem functioning

The various bits of knowledge acquired so far can be assembled so as to lead to an articulated theory of the functioning of marine systems. This procedure is typical of inductive science, albeit deriving from evidences produced by hypothetico-deductive approaches, and is another hypothesis at a higher hierarchical level, conducive of being tested and refined through holistic, ecosystem-based, integrated, crosscutting approaches (Arnaud et al. 2013).

Large-scale physical oceanography shows that the shallow Gibraltar current enters the Mediterranean Sea, causing a deep counter current of intermediate levantine water, flowing out from Gibraltar (Fig. 2), so coping with the unbalance between evaporation rates and freshwater riverine inputs. This water exchange affects only the first 500 m of the Mediterranean water column, having no influence on deeper waters that would rapidly become anoxic if new deep waters were not formed by the “cold engines” of the Northern Adriatic and of the Gulf of Lions, renewing spent deep waters (Fig. 2) by flowing into the deep sea through canyons, with the so-called cascading (Fig. 2a).

Small-scale physical oceanography shows that many canyons perpendicular to the coast can trigger coastward

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upwelling currents (Fig. 2b) forming circulation cells that connect the deep sea with the coast (Hickey 1995), acting as a system of smaller, auxiliary engines that might support the large-scale cold engines. The shape of coastlines, furthermore, generates other small-scale circulation patterns in form of gyres, eddies and fronts (Fig. 2c) that presumably have important roles in the functioning of ecosystems.

The morphology of both the coast and the sea bottom, hence, determines small-scale oceanographic circulation patterns that, coupled with large-scale circulation and riverine inputs, are at the base of ecosystem functioning. The mobilization and concentration of nutrients, in fact, trigger phytoplankton spring blooms, followed by zooplankton blooms that, in their turn, are the food of fish larvae, sustaining the recruitment of fish that, through intricate intra-ichthyic pathways, lead to the top of trophic networks (Godø et al. 2012) (Fig. 1). In the water column, thus, oceanographic patterns and processes determine particular habitats with original features, deserving the same attention as benthic ones.

Small-scale "engines" such as canyons generate benthic-pelagic coupling (as Della Tommasa et al. (2000) suggested), and eddies, gyres, and fronts that concentrate nutrients and organisms, can be considered as "cells of ecosystem functioning", with higher production rates than those at "neutral" areas, where these phenomena do not occur. Once putative cells of ecosystem functioning are identified, based on the features of the sea bottom and the coastline, it will be possible to test the prediction that these oceanographic processes lead to high-production rates throughout the food webs. The presence of endemic species in some canyons suggests a long history of isolation within the deeper parts of the cells (Gili et al. 1999), whose bio-ecological products might be very intense in restricted coastal areas just for a few days, to be then redistributed along the coast by surface circulation. The evaluation of the connectivity within and across cells of ecosystem function is the premise of any management and protection initiative stemming from knowledge-based approaches to our relationship with the environment.

5 The revolution of Good Environmental Status (GES)

Many national and international laws defined the status of the environment through physical, chemical and biogeochemical descriptors, easily measured with automated infrastructures. The 11 descriptors of GES of the European Marine Strategy Framework Directive radically change this approach: instead of considering the putative causes of impact, the new Directive considers their effects on the living component. Cumulative impacts, in fact, can lead to bad conditions even when the values of all the physical and chemical descriptors, taken one by one, are below the limits. The state of biodiversity is the first descriptor of GES, the impact of non-indigenous species on ecosystem functioning is the second, the remaining nine, even when they consider physical, chemical or geological variables, require proper functioning of the ecosystem, linked to a good state of biodiversity. Most of GES descriptors are not measured with current automated infrastructures, requiring approaches that recall the almost forgotten "natural history".

The identification of cells of ecosystem functioning will be crucial to evaluate the state of the environment, while considering that ecological processes are sharply seasonal, being linked to summer stratification of the water column and to the alterations of the mixed layer due to climate change.

Satellite evaluations of primary production provide information about what is happening at the surface, but are not conducive to understand what is happening in the water column, at higher trophic levels (Godø et al. 2012). What are the phytoplankton species that bloom in high-production zones (i.e. cells of ecosystem functioning)? What kind of zooplankton do they sustain? And how this is related to fish recruitment and, then, on the abundance and composition of the populations of fish and of other apical species of mammals, birds and reptiles? How these water movements allow for the closure of the biological cycles of the various species? Are the resting stages of plankters, for instance, re-circulated with the same processes that characterize biogeochemical cycles (Della Tommasa et al. 2000)? Do some species close their biological cycles using canyon-generated upwellings and downwellings to move from the deep sea to coastal areas and back, as proposed by Boero (in Canepa et al. 2014) for the mauve jellyfish *Pelagia noctiluca*? These questions, and many others, must be answered to evaluate the GES of marine systems through the study of biodiversity and ecosystem functioning.

The holistic approach, embracing all facets of marine science, aims at removing the conceptual barriers that prevent the full comprehension of marine systems. The separation of deep from shallow water, in this framework, does not have sense anymore, just as the separation between benthic and water column domains, or between plankton, benthos, and nekton or, again, the separation between microbial and macrobial systems (Boero et al. 1996; Boero and Bonsdorff 2007). In the past, many projects were aimed at understanding the detailed functioning of single portions of marine systems, or that linked some portions with each other, but only for some aspects. Novel synthetic approaches must produce models that assemble all available information in the light of a holistic view that, finally, envisages the oceans as a system of interconnected cells of ecosystem function.

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6 Observation systems

The descriptors of GES can be evaluated only through observation systems tailored on the features of the environment, so as to examine all relevant variables, even unexpected ones, with the aim of being ready to face deviations in the composition of biodiversity and in the functioning of ecosystems.

It is evident that simple monitoring, considering predetermined variables and using automated observation systems, is not suitable to recognize the causes of deviations from the expected "norms", leading to regime shifts or to alterations of what we might define as "normal" biodiversity composition and ecosystem functioning. Regime shifts are inherently unpredictable (Hastings and Wysham 2010) and are driven by unexpected phenomena. It is crucial, in this framework, to pass from closed monitoring systems, to open observation systems (Boero et al. 2014). Observation must rely on the technology employed in standard monitoring, with the awareness that this is necessary but not sufficient. Machines cannot perform observations that humans can easily make: monitoring systems, for instance, did not detect the jellyfish blooms that characterize Mediterranean ecosystems in recent years. The same is true for changes in the thickness of the mixed layer when thermal stratification is maximal. The evolution from monitoring to observation is a paradigm shift in the way the seas are studied, and must be pursued with coherence. Scientists, in this framework, are the key "sensors" of environmental quality, especially in the light of the definition of the ecological indicators of GES. The geographic distribution of marine stations, Marine Protected Areas, and other research structures and initiatives (e.g. citizen science) must become the backbone of our efforts to understand the structure and function of marine systems: a coherent and long-term network of marine observatories is urgent and necessary (Boero et al. 2014).

7 Current trends

If the future of historical systems cannot be predicted with mathematical precision (Boero et al. 2004), the depiction of scenarios is, however, possible. As Templado (2014) remarked, the MSE is going through important modification:

Tropicalization Non-Indigenous Species of warm-water affinity (tropical) become increasingly established.

Meridionalization The species that usually thrive in the southern part of the basin expand northwards, adding to tropical ones in changing northern biota.

Impairment of cold-water engines The Eastern Mediterranean Transient showed that, in a period of global warming, the cold engines might fail renewing deep Mediterranean waters, with vast consequences on MSE.

Changes in the phenology of species Reproductive patterns are modified by different thermal conditions: species of warm-water affinity have greater opportunities to grow and thrive than species of cold-water affinity.

Species extinction Cold-water species will be pushed in deeper waters, their surface populations having already suffered severe mass mortalities. The risk of extinction might be relevant (Boero et al. 2013b), but species might adapt to the new conditions (Boero et al. 2008b).

Less fish, more jellyfish and jellyfish eaters The fish-jellyfish transition is evident at a world scale, and MSE is not an exception. Boero (2013) "predicted" an increase of medusivorous organisms (such as sun fish and marine turtles), due to higher feeding opportunities.

Habitat destruction The cumulative effects of both direct (e.g. building maritime infrastructures) and indirect (e.g. pollution) impacts of human activities greatly contribute to habitat destruction (Claudet and Fraschetti 2010).

8 Future research

In this framework, the research priorities to detect patterns of events and to start to understand the processes that determine them are:

Explore biodiversity at species level This requires the production of new monographs on all groups, with large investments in capacity building in taxonomy (Terlizzi et al. 2003; Boero 2010).

Describe the functional traits of all species The morphological and genetic description of species is not enough; we must know their roles (Piraino et al. 2002), not to speak about the interactions among them.

Identify potentially threatened species This requires monitoring of records: if a species is not found since a long time, it is worthwhile investigating its status.

Map marine habitats After having agreed upon an operational habitat classification, habitats are to be mapped. Pelagic habitats must be recognized, based on current regimes and production patterns.

Identify hot spots of biodiversity A mosaic of different conditions is conducive to a great heterogeneity both in species and in habitat distribution; the cells of ecosystem function are crucial in this framework.

Improve the efficiency of Marine Protected Areas through networking Times are ripe to pass from the single MPA approach to the network approach, based on sound ecological principles.

Improve understanding of ecosystem functioning Biogeochemical explanations of ecosystem functioning are not sufficient to understand ecological processes, life cycles are

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crucial (Marcus and Boero 1998), together with unexpected interactions such as those hypothesized by Pati et al. (1999), who predicted that the meiofauna, feeding on the resting stages of planktonic organisms, might regulate plankton diversity, or by Della Tommasa et al. (2000) who predicted that canyons might be conveyor belts of benthic-pelagic fluxes of propagules, supporting coastal plankton pulses.

Focus on important poorly known processes Boero (2009) remarked that research focuses on easily tractable problems with a limited ecological importance in terms of ecosystem functioning, such as the grazing of limpets on algal mats, disregarding crucial phenomena, such as the grazing of pelagic tunicates on phytoplankton (Boero et al. 2013a).

Contingencies deserve more attention The disregard of contingencies hinders predictions about important phenomena such as the EMT or the fish-jellyfish transition. The demise of natural history was an unwise move (Boero 2011b).

Generate novel hypotheses stemming from natural history Fieldwork and observation must be the basis of models built on solid knowledge of the variables and of the interactions that connect them. Boero (2011b) showed possible alternatives to the current hegemony of disciplines that do not account for the historical nature of ecological problems.

Reconstruct the history of the systems Searching the archives and also using past artistic representations to compare current landscapes with those depicted in former times can lead to appreciate past situations and use them as reference.

Shift from monitoring to observation Monitoring is rigid and involves variables selected in advance and usually measured with machines. Observation is open to novelties, and must be based on the training of skilled technicians and scientists, continuously observing the state of the environment (Boero et al. 2014).

Involve the public in performing scientific research The public must become aware of the importance of science, being directly involved in exercises of citizen science also enhancing ocean literacy. The media must be heavily involved, and scientists must develop effective communication skills so as to influence strategic political decisions.

9 Conclusion

The approach described above, if sustained by proper action, is conducive to:

1. The elaboration of an integrated, holistic and ecosystem-based theory on the functioning of the Mediterranean Sea.
2. The definition of pilot areas where to test hypotheses whose outcomes might be extended to comparable areas.
3. The identification of cells of ecosystem function that might become management units, at different functional scales (single canyons, systems of canyons, straits, channels, promontories, river mouths, etc.).
4. The design of an observation network based on the features identified with the actions listed in the preceding points.
5. The production of guidelines for the management and protection of these systems, in relation with the socio-economic use of the goods and services of marine systems.
6. The definition of ecosystem baselines liable to detect trends linked to global change or to management actions.

The Mediterranean, just like the oceans of the world, is affected by global threats that cannot be removed with local action (e.g. global warming), but many pressures can be relieved with local or regional measures. Environmental costs must be internalized when accounting for the costs and benefits of any human enterprise, and the states of the so-called first world might start to live in a simpler way, being the first that should make sacrifices, since they profited from Nature benefits the most. In 2010, Pope Benedict XVI, in a speech in the Day of Peace, said: "Prudence would thus dictate a profound, long-term review of our model of development, one which would take into consideration the meaning of the economy and its goals with an eye to correct its malfunctions and misapplications. The ecological health of the planet calls for this, but it is also demanded by the cultural and moral crisis of humanity whose symptoms have for some time been evident in every part of the world". Scientists must warn decision makers about the situations we are facing in the future. We must admit that future telling is not in our powers, but we have sufficient knowledge and insight on the state of the environment to show that our way of living is not compatible with the well-being of ecosystems, and that our well-being depends on the well-being of ecosystems. The trend towards unsustainability is clear, and must be inverted with proper policies, based on a more rational use of natural resources and clean energy production. The Mediterranean and the Black Seas are miniaturized oceans and are showing rather dramatically the results of our direct and indirect pressures on ecosystems, calling for novel ways to tackle the complex problems regarding our impacts on the interaction between the physical and the biological domains in marine environments.

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