
The Marine Biodiversity of the Mediterranean Sea in a Changing Climate: The Impact of Biological Invasions

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Abstract

The Mediterranean Sea, one of the most complex marine ecosystems, is inhabited by a rich and diverse biota which is disproportionate to its dimensions. It is currently affected by different pressures, mainly driven by human activities such as climate change and bioinvasions. This Sea, also due to its geographic position (wedged between the temperate climate of central Europe and the arid climate of northern Africa), seems to be one of the regions most susceptible to global climate change. The increased rates of introduction and spread of marine alien species may represent a supplementary stress factor to Mediterranean marine native biota already challenged by climatic abnormalities. The Suez Canal is considered to be the main vector of introduction of non-indigenous marine species into the Mediterranean Sea. Due to the dramatically accelerating rate of such introductions and due to the sheer magnitude of shipping traffic, the Mediterranean Sea may be considered as a true hotspot of marine bioinvasions. The complexity of interactions between native and invasive species and the associated resulting impacts make environmental management of such an issue particularly difficult. A collaboration between researchers, resource management agencies and policy makers is called for to bolster the effectiveness of invasive species management procedures.

Keywords: climate change, invasive alien species (IAS), management measures, marine biodiversity, Mediterranean Sea

1. Introduction

The Mediterranean Sea, a 'sea in the middle of the land' (**Figure 1A**), a semi-enclosed sea at the crossroads between Europe, Africa and Asia, represents just 0.82% of the surface area of the

world's oceans [1]. It is the deepest (average 1460 m) and largest (2969.000 km²) enclosed sea on Earth [2] and from space looks like a narrow lake, stretching 3800 km from East to West and 800 km from North to South. Hot dry summers and low input from rivers make it a concentration basin. The Mediterranean Sea has a slight interchange of waters with the Atlantic Ocean through the Strait of Gibraltar in the west and with the Black Sea and the Sea of Marmara through the Dardanelles in the North-East [2]. The Strait of Gibraltar plays an important role in the circulation and productivity (the rate of generation of organic matter) of the Mediterranean, an extremely oligotrophic sea (largely due to a poor nutrient supply) [3]. Indeed, Atlantic surface waters, after having circulated within the Mediterranean in an anticlockwise direction, flow out denser and deeper below the entering waters in the form of the Mediterranean outflow water (MOW). As one progressively moves east into the Mediterranean Basin, oligotrophy increases whereas the productivity decreases. The Suez Canal, within the Levantine Basin, opened in 1869, provides an artificial navigable connection with the Red Sea and the Indo-Pacific Ocean. The Strait of Sicily, separating the island of Sicily from the coasts of Tunisia, is generally considered as the boundary zone between the two main sub-regions of the Mediterranean Sea, the Western and the Eastern, previously placed in the mid Ionian Sea [4]. The two sub-regions are divided into four main sub-basins (western Mediterranean, Adriatic Sea, Ionian Sea and Aegean-Levantine Sea), characterized by distinctive hydrodynamics and water circulation patterns.

The turbulent past geological events and a kaleidoscope of climatic and hydrologic conditions make this Sea one of the most complex marine ecosystems, at the crossroads of different biogeographic provinces [5], inhabited by a rich and diverse biota [2], currently affected by different pressures, mainly driven by human activities. The most important threats to Mediterranean biodiversity are habitat modification and loss, climate change, pollution, coastal urbanization, overexploitation and alien species, that is, organisms that arrive in a region beyond their native range due to direct or indirect human intervention [2, 6].

In this chapter, on the basis of a review of the available literature, we analysed (a) the origin of the Mediterranean Sea as well as the origin of its rich and diverse biota; (b) the main threats to Mediterranean biodiversity, focusing on climate change, one of the main drivers of the ongoing change in Mediterranean biodiversity; (c) the phenomenon of biological invasion (mediated through the entry of invasive alien species (IAS), which spread widely and cause environmental, economic, or human health impacts) in the Mediterranean Sea, particularly stressing impacts on ecosystems and pathways of introduction. Finally, we provide summaries for 10 invasive species known worldwide for their environmental and economic impact and we suggest possible actions to prevent and manage this phenomenon.

2. History of the Mediterranean Sea

The Mediterranean Sea is the result of a tormented geological history dating back around 230 million years before present (hereafter, myr BP), when a large single landmass Pangea and a large ocean Panthalassa co-existed (**Figure 1B**). When this landmass started breaking up, an eastward-open equatorial ocean, the Mediterranean Sea ancestor, inhabited by a highly diverse biota

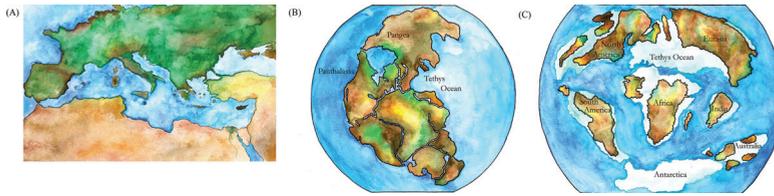


Figure 1. (A) The Mediterranean Sea, (B) Pangea and Panthalassa, (C) The Tethys Ocean (drawings Lucia Gastoldi).

of warm-water origin, was formed. The formation of this ocean—called Tethys—divided the Pangea into the Laurasia continent to the North and the Gondwana continent to the South and connected the Mediterranean connection with the Atlantic Ocean to the Indo-Pacific Ocean (**Figure 1C**). Around 130 myr BP (Cretaceous), the connection with the Indo-Pacific Ocean was interrupted. Subsequently, around 45 myr BP (Eocene), the original Tethys became smaller as a consequence of African and Eurasian plate collisions, responsible also for the formation of the Alps and Himalayas. Twenty-five myr BP (Miocene), the African plate made contact with the Eurasian plate, dividing the Tethys Sea into two parts: the ancestor of the Mediterranean Sea in the South and the so-called Paratethys in the North-East. Both seas underwent significant reductions and the Paratethys remnants formed the Black, the Caspian and the Aral Seas. When the narrow Isthmus of Suez was formed and the connection with the Indian Ocean was interrupted (around 13 myr BP, Miocene), this water body slowly lost its tropical biota. During the Miocene (6–7 myr BP), the connection (the Gibraltar Strait) with the Atlantic Ocean was closed as a consequence of a collision between Africa and the south-western segment Eurasian plate. This event, responsible for a significant negative water balance, led the Mediterranean Sea to dry up, ending up in the form of a series of hypersaline lakes separated by vast expanses of exposed sandy seabed (the so-called Messinian Salinity Crisis, around 5.6–5.5 myr BP). This spectacular event caused a severe reduction in the original rich biota and the disappearance of several paleotropical elements, even though a few elements were able to survive in refuges. Around 5 myr BP (Pliocene), the Strait of Gibraltar opened once again, allowing the waters of the Atlantic Ocean to flood the Mediterranean, repopulating it exclusively with species of Atlantic origin [5]. During the Quaternary, the alternation of glacial periods with warm interglacial periods allowed the influx into the Mediterranean of Atlantic species of boreal or subtropical origin [1].

3. The Mediterranean: a hotspot of biodiversity under threat

Currently, biodiversity is widely expressed as species richness (number of species occurring in a specific area), a term considered as a valuable indicator of environment health [7, 8]. Since marine ecosystems have probably received less attention than their terrestrial counterparts, the number of marine species is currently still considerably lower than that of terrestrial species [9].

The Mediterranean Sea, even though representing a small part of the world's oceans, is inhabited by an unusually rich and diverse biota. It hosts approximately 17,000 species, representing 4–18% of the world's marine biodiversity, and includes temperate, cosmopolitan, subtropical,

Atlantic and indo-pacific taxa [1, 2]. As a result, the Mediterranean Sea is considered as a true hotspot of biodiversity [1, 2, 10], even by virtue of the high rates of endemism it supports (an estimated 20–30% of marine species in the Mediterranean are considered endemic to the Basin [10]). The high marine biodiversity of the Mediterranean Sea may be due to different reasons: for example, it has been more intensively studied than the other seas; its tormented geological history and the numerous climatic and hydrologic events that led to the co-occurrence of temperate and subtropical species [1]. The low sea water temperatures during the glacial periods greatly contributed to the invasion of cold-water species from the northern Atlantic. The preponderance of species of Atlantic origin within the current Mediterranean, as a result of the reopening of the Strait of Gibraltar, makes the Sea, from a biogeographic point of view, an Atlantic Province. The opening of the Suez Canal coupled with a rise in sea temperature increase led to the settlement of thousands of tropical species, either in the form of 'Lessepsian migrants', named after Ferdinand de Lesseps, a French diplomat and designer of the Suez Canal [11], or as 'Erythrean aliens' [12]. According to [13], the current high Mediterranean settlement of tropical species coming from the Suez Canal is tantamount to a re-colonization by Tethyan descendants rather than an invasion by alien species. Sea warming is also responsible for the increase in the ingression of Atlantic thermophilic species into the Mediterranean through the Gibraltar Strait, the so-called 'range-expanding species'. The introduction of thousands of tropical species into the Mediterranean is without doubt the most remarkable biogeographic phenomenon within today's Basin [13]. With respect to marine biodiversity, an evident heterogeneity between the marine species composition of the western and eastern basins exists. In particular, we observe that in the western part of the Mediterranean Sea the biota composition is influenced by the Atlantic Ocean, whereas in the Levant Sea, this is strongly linked to the Red Sea. The western Mediterranean shows the highest species richness followed by the central basin, the Adriatic and Aegean Seas, and the Levantine basin, which is more influenced by species introduction through the Suez Canal and which displays the lowest values [10]. Endemic marine species in the Mediterranean either consist of rare paleo-endemisms of Tethyan origin (i.e. they precede the Messinian Salinity Crisis) and of more frequent neo-endemisms of Pliocene origin. The western basin shows a higher rate of endemism than the eastern basin, appearing to be an active centre of endemism [10]. The neo-endemism *Cystoseira*, considered a key-stone genus, presents 21 species endemic to the Mediterranean [14]. In particular, the paleo-endemic *Caulerpa sedoides* is confined to the coasts of Algeria, Tunisia, and the Island of Pantelleria. Another paleo-endemism, the seagrass *Posidonia oceanica*, could be considered a Messinian species, that is, a species which persisted, probably in refugia, when the Mediterranean dried up.

Nowadays, changes in the Mediterranean biodiversity are essentially driven by human activities. The Mediterranean is amongst the most impacted regional sea areas, as a consequence of different anthropogenic pressures on different coastal and marine ecosystems within the Basin: habitat modification and loss, climate change (e.g. warming, acidification and sea level rise), pollution, coastal urbanization, overexploitation and the intentional or indirect introduction of alien species (synonyms: exotic, non-native, non-indigenous, and allochthonous) [2, 6, 15, 16]. Habitat modification and loss, pollution and overexploitation are considered to be the main threats to marine biodiversity and natural ecosystem functioning in the Basin, but other threats such as climate change and invasive species (the most insidious of alien species) introductions are similarly expected to have significant impacts [5, 17, 18]. In the Mediterranean Sea, several valuable and unique habitats,

supporting an extensive repository of biodiversity, are also under threat [19]. A recent study showed that coastal areas and shelves are the most threatened habitats, and the areas of highest concern are concentrated in the northern region [18]. The Mediterranean Sea represents the highest proportion of threatened marine habitats in Europe (32%, 15 habitats) with 21% being listed as vulnerable and 11% as endangered. Among the endangered habitats, we find, for example, the photophilic communities consisting of canopy-forming algae in the infralittoral and upper circalittoral rock, whereas the following habitats are considered vulnerable: biogenic habitats of Mediterranean mediolittoral rock, photophilic communities dominated by calcareous, habitat-forming algae, and *Posidonia* beds in the Mediterranean infralittoral zone.

4. Climate change and its effects on Mediterranean biodiversity

Global climate change and its associated impacts on the marine domain, for example, sea warming, ocean acidification, and sea level rise (at the rate of about 1 mm per year), is an ongoing phenomenon which is certainly affecting biodiversity, human activities and health, but we do not know exactly how profound the consequent changes in marine ecosystems will be [6, 20]. Climate change, may act at different biological levels: individual, population, and ecosystem. In particular, species with a low dispersion ability are highly affected by climate change, which may also lead to local extinctions, greatly contributing to biodiversity loss. The Mediterranean Sea, also due to its geographic position between the temperate climate of central Europe and the arid climate of northern Africa, seems to be one of the most vulnerable regions to global climate change but we don't know if all sub-basins will be equally affected by this phenomenon [6, 20]. The Mediterranean climate is expected to become warmer and drier with an increase in inter-annual variability due to extreme heat and drought events [20–22]. Even though the Mediterranean Sea is probably entirely affected by this warming trend, data on this phenomenon are mainly reported for the north-western Mediterranean [6]. Mediterranean temperature anomalies observed during summer 1999 and 2003 led to catastrophic mass mortality events, in particular of benthic invertebrates (e.g. sponges, gorgonians, bryozoan and molluscs) [23–25]. The 2003 event resulted in mortality of *P. oceanica* but also in large-scale flowering episodes for this seagrass [26, 27].

Sea warming may also have effects on the virulence of pathogens, as observed for *Vibrio shiloi*, responsible for the whitening of the coral *Oculina patagonica* in the eastern Mediterranean [28]. Moreover, it is responsible for the expansion of toxic dinobionts such as *Ostreopsis ovata*, which produces palytoxins, a serious public health hazard [6]. Temperature anomalies seem also to negatively affect the chemical defences of marine organisms [29], allowing pathogens to act undisturbed. The warming trend experienced by the Mediterranean is also influencing the distribution of its marine native species, with some (e.g. *Thalassoma pavo*) embarking on a westward range expansion within the same basin, the so-called 'meridionalisation' phenomenon as opposed to the 'tropicalisation' of Mediterranean marine biota fuelled by the invasion of Lessepsian migrants [6]. Tropical species, that is, Lessepsian migrants or those of Atlantic origin, have long been confined to the extremities of the eastern Levantine or western basin, but as a consequence of the warming trend of the Mediterranean as well as the ever-expanding shipping networks and volumes, they are rapidly spreading throughout the entire basin [2].

Warming may also lead to the decrease or extinction of cold-water boreal species which cannot migrate further northwards and seek deeper waters, as is the situation in the Adriatic.

The increased introduction and spread of alien species may represent a supplementary stress factor for native species already weakened by climate variations.

The rise of dissolved carbon dioxide, lowering the pH of the ocean waters, is altering the sea-water carbonate system, as part of the so-called 'ocean acidification' phenomenon, which may affect organisms and ecosystem functioning [30]. Calcifying organisms (planktonic and benthic) such as corals, foraminifera, coccolithophores and coralline red algae, important depositors of calcium carbonate, may be hampered under increasing levels of water acidity in their attempts to synthesize their calcium carbonate shell or skeletons [31]. Coralline red algae, contributing to the formation of coralligenous habitats and coastal reefs, are particularly sensitive to ocean acidification, partly because they are composed of high magnesium-content calcite, the most soluble form of CaCO_3 [32]. The decline in coralline red algae is particularly significant for the ecosystems they form and for the carbonate cycle in general [33].

Moreover, we have to consider that climatic factors may act in combination and/or interact with other factors such as pollution and overexploitation. Acidification and warming, for example, may exert synergistic effects on the calcification rates of corals and crustose coralline algae [33].

5. Alien species in the Mediterranean Sea: pathways and impacts

Alien taxa are species, subspecies or lower taxa introduced outside of their natural, past or present, range and outside of their natural dispersal potential. Their presence in the given region is due to direct or indirect (e.g. passive dispersal through a man-made shipping canal) introduction by humans [34]. A common denominator amongst the new arrivals within the Mediterranean is their thermophilic affinity, being native of warmer sea regions, such as the Red Sea or the Indo-Pacific region for the so-called 'Lessepsian' migrants or the sub-tropical equatorial Atlantic for the 'range-expanders' coming in through the Straits of Gibraltar [35]. According to the convention on biological diversity (CBD), the compilation and dissemination of information on alien species that threaten ecosystems, habitats or species is a priority [36]. The estimate for new introductions in the Mediterranean is constantly being revised and may be as high as 1000 species. The majority of alien species in the Mediterranean are of Indo-Pacific origin (41%), followed by those of Indian Ocean (16%) and Red Sea (12%) origin; some species have a pantropical or circumtropical distribution (19%) [2]. The number of alien species differs among the Mediterranean sub-regions (the Eastern, the Western, the Central and the Adriatic Sea) described under the Marine Strategy Framework Directive [37]. The majority of alien species occurs in the Eastern sub-region, with lower numbers being registered in the Western and Central sub-regions and in the Adriatic Sea [15].

Alien species are entering the Mediterranean Sea naturally or as directly mediated through human activities. Three main mechanisms of introduction for non-indigenous species (NIS) are currently recognized (Convention on Biological Diversity: [38]): wilful importation as a

commodity, arrival via a transport vector or unassisted spread from a neighbouring region through man-made channels and canals, for example. Six pathways are associated to these mechanisms: commodities intentionally released or escaped (e.g. aquaculture, botanic gardens, agriculture and aquarium trade) or contaminants of commodities (seeds and fisheries) unintentionally transported, transport-stowaway (shipping), corridors (man-made marine or inland canals) and secondary natural spread of species introduced through the other pathways [38].

The Suez Canal is considered to be the main vector for marine introductions into the Mediterranean Sea. The Suez Canal in fact has been responsible for 53% of all exotic marine species entering the Mediterranean, and some species (11%) initially entered through the Suez Canal but were later dispersed within the Basin by vessels [2]. Prior to the opening of the Suez Canal, the entry of 'Lessepsian migrants' was insignificant due to the existence of a high salinity barrier, constituted by the Bitter Lakes which stymied the passive entry of species through this route, but later, with the construction of the Aswan Dam, this barrier ceased to exist, allowing the migration of hundreds of Red Sea organisms. The widening of the existing canal at Suez in 2015, so as to cater for increased volumes of shipping, is expected to have a strong impact on the Mediterranean marine ecosystems [39].

The rates of introduction of new marine species through the Bosphorus are negligible, especially when compared to those through the Strait of Gibraltar and the Suez Canal.

Transportation via shipping-related infrastructure, for example, ballast waters, ballast tanks, anchors and fouling, is expected to increase as a result of our increasing reliance on maritime trade, and is the second vector of introduction in terms of importance. Even though the majority of the vessels originate in North Atlantic ports, North Atlantic species represent only 14% of the alien biota entering the Basin, whereas around 50% are of Indian and Indo-West Pacific origin. That is probably due to the differences or similarities in salinity and temperature between these two areas of origin and the Mediterranean Sea. Research vessels and platforms for offshore oil and gas exploration may also contribute to the spread of alien species [40]. Due to the important role played by shipping, ports and adjacent areas may be considered as 'hotspots' of biotic invasion. Shipping is also important as a vector for secondary introduction; for instance, *Sargassum muticum* and *Caulerpa taxifolia* have been spread in the Mediterranean through fishing and recreational vessels [41, 42]. The Mediterranean biodiversity is particularly vulnerable to shipping impacts such as pollution, anchor damage and introduction of exotic species, due to the high volume of shipping within the Basin, which greatly expanded over the past half century and which is expected to grow in the next years. The current ongoing intensive movement of people and goods contributed to greatly increase the rate of spread of invasive species [43].

The aquaculture industry represents the third vector of introduction but probably it could be more important than previously thought as a consequence of the unintentionally introduced species, for example, attached to the intentionally introduced species. Introductions through the aquarium trade, involving more freshwater species than marine ones, represent only a small fraction of the total number of invasive species, but these are on the increase due to the popularity of household marine aquaria. Here again, the number of alien species entering as a consequence of aquarium trade is probably higher than that officially reported

[44], also because many alien species previously assigned to other introduction pathways could in fact have arrived via aquarium trade.

However, it is not always possible to identify with certainty the pathway for a species introduction, except for intentional introductions, also because an introduction may have occurred through multiple pathways or stages. Even worse, assigning a native or non-indigenous status to a species might not even be possible, as is the case for cryptogenic species, whose origins are unknown.

Whatever is the pathway of introduction, when an alien species become established, that is, capable of reproducing and maintaining self-perpetuating populations in the wild, it is really difficult to extirpate it completely [45]; hence, prevention, for example, removal of pathways, is the only effective action for reducing the introduction and spread of alien species.

However, the rise of establishment conditions for an alien species does not necessarily translate into invasion success. The success of alien species may depend on the biological characteristics and the dispersion vectors of the species, and the susceptibility of the receiving habitat, for example, availability of niches, low species richness, physical and chemical conditions, release from competitors and parasites [46, 47]. For example, rich and highly structured ecosystems are more resistant to invasion than poor and disturbed ones [48].

It has been ascertained that alien species may have significant environmental, socio-economic and human health impacts [49–52]; consequently, globally, they are recognized as one of the major threats to biodiversity. However, it is not always true that 'native is good, alien is bad'. Some alien species may have positive effects on native biodiversity and can enhance or provide new ecosystem services [53]. Alien species may affect native biota directly or indirectly and may act at different levels, that is, at the gene, individual, population and community level [54]. Moreover, alien species impacts can vary spatially and temporally, that is, there is a lag between alien population growth and native species response [55, 56]. The impacts of alien species generally increase when they are established and they spread in the new environment, but they may also have impacts at the initial stages, as soon as they are introduced [57, 58]. The level of the impact of an alien species may vary considerably, ranging from a negligible to a profound impact. Indeed, many alien species are known for having caused significant changes in native ecosystems, whereas others apparently have had little or no visible effects on receiving environments [58, 59]. Moreover, very often, the impacts become visible long after the onset of invasion or they are not well known, even though some effects are visible. Conversely, the effect of the introduction of a herbivore, which overgrazes algal communities, for example, is easy to detect. To plan effective management actions against biological invasions, a system for evaluating, comparing and possibly predicting the level of impact of different alien species is essential. Recently, a dynamic method for classifying alien species on the base of the level of their environmental impacts (ranging from 0 to 5), considering their impact mechanisms, for example, rates of herbivory, competition and impact on ecosystems, was proposed [51] and adopted by IUCN (International Union for Conservation of Nature). Since it is not always easy to assess and/or predict the impact of alien species, readily accessible information on spread ability and ecological impacts is also necessary.

6. Invasive alien species (IAS) in the Mediterranean Sea

Invasive alien species (IAS) are those alien taxa that have established large populations, significantly expanding their range, and/or exert substantial negative impact on native biota, for example, substitution of native species, biodiversity loss, habitat modifications and alterations in community structure, socio-economic amenities, or human health [53, 60–64]. According to the ‘tens rule’ proposed by Williamson [65], approximately 10% of all introduced species in a given area will become established, and approximately 10% of established species will become invasive. Currently, invasive species are considered as one of the main causes of biodiversity loss after habitat destruction [2, 62]. Even though the impact of most invasive species remains unknown [47], they are regarded worldwide as a threat. Due to the dramatically accelerating rate of species introductions, the Mediterranean Sea may be considered a true hotspot of marine bioinvasions [66], and marine protected areas (MPAs) within the Basin have not been spared this environmental hazard. To date, almost 1000 marine non-indigenous species (NIS) have been introduced in the Mediterranean, of which more than half are considered to be both establishing and spreading, criteria that categorize them as invasive species [67].

The success of invasive species in the new areas is linked to some peculiar characteristics such as the capacity to thrive in different environments, to tolerate a wide range of environmental conditions, to exploit a variety of food sources, together with their high growth and reproduction rates and the lack of natural predators [68]. However, possession of these characteristics does not automatically translate into a successful invasion. Indeed, the success of invaders within a new area to which they are introduced is not predictable [69].

Many inventories of alien/invasive species have been compiled to date. In order to guarantee the scientific quality of the information constituted by these inventories, a guide for identifying the causes of uncertainty that can negatively affect data quality, as well as a protocol to select eligible records for such inventories, based on standardized criteria, was recently proposed [70].

We report subsequently on the impacts of a selected group of marine species featuring in the list of 100 ‘worst’ Invasive Alien Species of the Mediterranean [71], mainly belonging to zoobenthos (particularly Mollusca, fish and Crustacea) and phytobenthos.

Among the macroalgae, *Caulerpa* species are well-known invaders in the Mediterranean. They have been reported to cause serious problems to native marine ecosystems [72]. They are able to compete with native key species [73], becoming the dominant species themselves, but they are also known to have negative impacts on commercial and recreational fishing.

Turf algae such as *Womersleyella setacea* and *Acrothamnion preissii*, reported to seriously change native communities and to clog up fishing nets and gear [74], may exert a considerable socio-economic impact. Several invasive bivalves, imported for mariculture purposes, are well known for their negative impacts on native marine ecosystems, as is the case of the Pacific oyster *Crassostrea gigas*, considered to be the culprit behind the most spectacular invasion in the Venice lagoon [75]. These bivalves, forming over time consolidated biogenic reefs, may act as ‘ecosystem engineers’ [71]. The jellyfish *Rhopilema nomadica* has been reported to negatively affect coastal installations, fisheries, human health and tourism [76].

The Atlantic species *Percnon gibbesi* has spread rapidly in the Mediterranean ever since its first record from the island of Linosa in the central Mediterranean in 1999 [77] and is probably the most invasive decapod species in the region. It consumes primarily algae such that it may seriously affect the structure of algal assemblages within a given area, and it may also compete with native species for food and shelter [78].

Invasive dinoflagellates such as *Alexandrium catenella*, *O. ovata* and *Coolia monotis* exert serious impacts on human health but also on tourist activities in the areas where they occur [79]. Invasive fish species also represent a serious public health hazard, for example, *Lagocephalus sceleratus*, is a potential risk to humans, since it contains tetrodotoxin (TTX) that may be a source of food poisoning [80].

7. Ten of the worst marine invasive species

We present subsequently the descriptive summaries for 10 invasive species known worldwide for their environmental and economic impact. Phytobenthos: *C. cylindracea*, *S. muticum*, *Undaria pinnatifida*, *W. setacea*. Zooplankton/Cnidaria: *R. nomadica*. Zoobenthos/Mollusca: *Brachidontes pharaonis*. Zoobenthos/Crustacea: *P. gibbesii*. Zoobenthos/Fish: *Fistularia commersonii*, *L. sceleratus*, *Pterois volitans*.

The species are grouped into phytobenthos, zooplankton and zoobenthos. For each species, we report a photograph, a description of the main morphological and ecological characteristics, the origin, the first Mediterranean record, the distribution in the Mediterranean (as species may spread quickly, this information may soon become out of date), the likely pathway of introduction and spread, and the potential or documented impacts [68, 81–86].

7.1. Phytobenthos

Scientific name: *Caulerpa cylindracea* Sonder, 1845 (**Figure 2A**).

Classification: Chlorophyta (*Ulvophyceae*, *Caulerpaceae*).

Common name: grape algae.

Description: a green algae with a creeping axis (stolon), attached to the substratum by numerous short rhizoids, and bearing erect axes (fronds) slightly inflated above their attachment to the stolon. Fronds, up to 20 cm high, bears rounded, vesicular branchlets (also called ramuli).

Ecology: Subtidal communities, on all kinds of substrata, from 0 to 70 m depth.

Origin: Australia and New Caledonia.

First Mediterranean record: in 1990 off the coasts of Libya [87].

Distribution: throughout the Mediterranean.

Mode of introduction: remains unknown; however, maritime traffic and the aquarium trade are the most likely vectors for its introduction.

Impacts: Invasive species that competes with native species and may change native benthic communities. There are also reports of fishing nets being clogged and broken by this algae.

Scientific name: *Sargassum muticum* (Yendo) Fensholt, 1955 (**Figure 2B**).

Classification: Ochrophyta (Phaeophyceae, Sargassaceae).

Common name: Japanese wireweed.

Description: Algae up to 4 m high, attached to the substratum by a discoid holdfast; axis erect and spirally branched with leaf-like simple branchlets; subspherical air vesicles; cylindrical and smooth receptacles.

Ecology: Shallow subtidal communities. It can form floating mats on the sea surface.

Origin: North-western Pacific.

First Mediterranean record: in 1980 from France, Etang de Thau [88].

Distribution: Balearic Islands, Corsica, France, Italy, Spain.

Mode of introduction: unintentionally, with imported oysters likely from Japan.

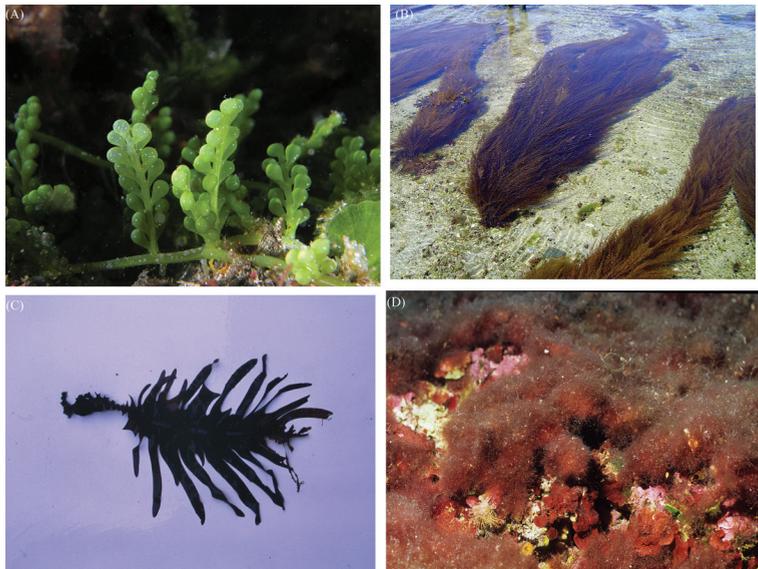


Figure 2. (A) *Caulerpa cylindracea* (photo Fabio Russo), (B) *Sargassum muticum* (photo Conxi Rodríguez-Prieto), (C) *Undaria pinnatifida* (photo: Ester Cecere and Antonella Petrocelli), (D) *Womersleyella setacea* (photo: Enric Ballesteros).

Impacts: Invasive species. It is a fouling organism. There are reports of fishing nets being clogged and interferences with propellers and intakes.

Scientific name: *Undaria pinnatifida* (Harvey) Suringar, 1873 (**Figure 2C**).

Classification: *Ochrophyta (Phaeophyceae, Alariaceae)*.

Common name: sea mustard or wakame.

Description: Sporophytes up to 1 m high, with a simple stipe continuing as a midrib through the lanceolate blade. Sporophylls along the stipe. Gametophyte microscopic.

Ecology: shallow subtidal communities. Annual.

Origin: North-western Pacific.

First Mediterranean record: in 1971 from France, Etang de Thau [89].

Distribution: France, Italy.

Mode of introduction: unintentionally, with imported oysters from Japan.

Impacts: Invasive species that cause problems to aquaculture and shipping.

Scientific name: *Womersleyella setacea* (Hollenberg) R.E. Norris, 1992 (**Figure 2D**).

Classification: *Rhodophyta (Florideophyceae, Rhodomelaceae)*.

Common name: not assigned.

Description: Small filamentous algae (up to 1 cm high) with cylindrical axes. It forms mats of prostrate and erect branches. Prostrate filaments anchor the thallus to the substrate by means of rhizoids that terminally form a multicellular disc. Erect branches are poorly ramified.

Ecology: Subtidal communities. Usually epiphytic and forming perennial, dense tufts on native communities by modifying benthic assemblages and outcompeting key native species (i.e. *Paramuricea clavata*, *Cystoseira* and sponge species). Forms dense cover on coralligenous habitat.

Origin: Pacific Islands.

First Mediterranean record: in 1986 from Italy, Livorno [90].

Distribution: Alboran Island, Balearic Islands, Corsica, Croatia, Cyprus, France, Greece, Italy, Maltese Islands, Monaco, Rhodes Island, Spain.

Mode of introduction: shipping or accidental escape from an aquarium.

Impacts: invasive species that competes with native species. Its mats lead to an impoverishment of subtidal communities. There are also reports of fishing nets being clogged.

7.2. Zooplankton/Cnidaria

Scientific name: *Rhopilema nomadica* Galil, Spanier & Ferguson, 1990 (**Figure 3A**).

Classification: *Cnidaria (Scyphozoa, Rhizostomatidae)*.

Common name: nomad jellyfish.

Description: A neritic epipelagic, swarming jellyfish. The bell is up to 90 cm in diameter, usually 40–60 cm. The body is light blue with blunt tuberculation of the exumbrella. The mouth arms end in vermicular filaments.

Ecology: can form dense aggregations in coastal areas during summer months, although it can also appear all year round. It has a two-stage life cycle consisting of a swimming medusa stage and a benthic polyp stage (the scyphistoma). Depending upon food availability and other environmental variables, the scyphistomas form large numbers of pelagic medusas.

Origin: Originally from East Africa and the Red Sea.

First Mediterranean record: in 1976 from the coasts of Israel [91].

Distribution: Egypt, Greece, Israel, Lebanon, Turkey, Malta, Tunisia.

Mode of introduction: entered the Mediterranean through the Suez Canal.

Impacts: It is a voracious predator that consumes vast amounts of shrimp, mollusc and fish larvae and can cause major trophic cascades in the marine food web, with a resulting impact on biodiversity. It can inflict painful injuries to bathers. Furthermore, large swarms can clog fishing nets, consequently reducing catches, and block cooling water intakes of coastal industrial facilities and desalination plants.

7.3. Zoobenthos/Mollusca

Scientific name: *Brachidontes pharaonis* (P. Fischer, 1870) (Figure 3B).

Classification: Mollusca (*Bivalvia*, *Mytilidae*).

Common name: rayed erythrean mussel.

Description: A small gregarious intertidal bivalve with a 40-mm shell, externally dark brown-black and internally violet-black. Shell equivalve, inequilateral, attached to substrate by stout byssus. Sculpture of numerous fine radial bifurcating ribs, which become coarser posteriorly and margin crenulate. The hinge has dysodont teeth.

Ecology: Suspension feeders. Lives in shallow water (at sea level or just below) attached by



Figure 3. (A) *Rhopilema nomadica* (photo: Maria Ghelia), (B) *Brachidontes pharaonis* (photo: Bella Galil), (C) *Percnon gibbesi* (photo: Fabio Russo).

its byssus to rocks and stones, mostly in clusters. It may reach very high densities and cover completely a rocky shore.

Origin: Indian Ocean, Red Sea.

First Mediterranean record: in 1876 from Egypt, Port Said [92].

Distribution: Egypt, Lebanon, Israel, Italy, Greece, Syria, Turkey, Rhodes, Cyprus, Croatia.

Mode of introduction: propagules entered the Mediterranean through the Suez Canal. Ship transport as a major vector.

Impacts: Locally invasive. Can deplete the phytoplankton concentration in the water column, constraining the growth of other filter-feeding animals such as *Mytilaster minimus*. Dense mats of these bivalve populations in industrial facilities and salt works might result in high-energy consumption and economic losses.

7.4. Zoobenthos/Crustacea

Scientific name: *Percnon gibbesi* (H. Milne Edwards, 1853) (Figure 3C).

Classification: *Arthropoda* (*Malacostraca*, *Percnidae*).

Common name: sally lightfoot crab.

Description: This mimetic, relatively small crab is up to 3 cm across. Its body is flat and square-shaped with a smooth surface. The carapace is brownish green and the long, flattened legs are banded with golden yellow rings. The ventral surface is pale. The walking legs have a row of spines along the leading edge. The eyestalks and claws are orange.

Ecology: It occurs along shallow infralittoral rocky shores, under boulders, or in narrow crevices. It is an opportunistic herbivorous feeder, consuming filamentous and calcareous algae, and the fine film of algal growth. But it may also feed on animal food such as pagurids, polychaetes, gastropods, crustaceans and jellyfish.

Origin: Atlantic Ocean.

First Mediterranean record: in 1999 from Italy, Linosa Island and the Balearic Islands [77, 93, 94].

Distribution: Albanian, Montenegro, Italy, Balearic Islands, Malta, Crete, Greece, Turkey, Libya, Tunisia, Algeria, Cyprus, Israel, Lebanon.

Mode of introduction: It may spread in the ballast waters of ships and on fishing nets as well as being transported in its larval stage by water currents.

Impacts: Its widespread and expanding distribution along the Mediterranean coasts and the high rates of increase in abundance tell us that it is a highly invasive species. Since its habitat overlaps with those of native *Pachygrapsus marmoratus* and *Eriphia verrucosa*, exclusion of native crabs may occur in some areas.

7.5. Zoobenthos/Fish

Scientific name: *Fistularia commersonii* Rüppell, 1838 (**Figure 4A**).

Classification: Chordata (Actinopterygii, Fistulariidae).

Common name: bluespotted cornetfish.

Description: a fish with a grey to olivegreen body, commonly 20–100 cm long (max. 150 cm). The body is extremely elongated, becoming depressed after head, which is very long. Snout tubular and long, ending in a small mouth. Teeth are very small. Dorsal and anal fins are posterior in position, opposite to each other. The skin is smooth, without bony plates along the midline of the back.

Ecology: Lives solitary or in small groups, near reefs. Feeds mainly on fish as well as on squids and shrimps.

Origin: Indo-Pacific and eastern central Pacific.

First Mediterranean record: in 2000 from Israel [95].

Distribution: Turkey, Rhodes Island, Crete, Greece, Italy, Algeria, Spain, Libya, Cyprus, Israel, Tunisia.

Mode of introduction: Entered the Mediterranean through the Suez Canal.

Impacts: It is an extremely voracious predator and is aggressive when in schools. It preys on native commercially important fish. Its rapid increase in abundance may potentially have adverse effects competing with native fish communities by exploiting local resources faster.

Scientific name: *Lagocephalus sceleratus* (Gmelin, 1789) (**Figure 4B**).

Classification: Chordata (Actinopterygii, Tetraodontidae).

Common name: silverstripe blaasop.

Description: The body is elongated (20–85 cm), somewhat compressed laterally and inflatable. The body is brownish in colour with black, regularly distributed spots of equal size dorsally; a conspicuous wide silver band is present on the lower parts of the flanks, from the mouth to the caudal fin. The head is large with a blunt snout.



Figure 4. (A) *Lagocephalus sceleratus* (photo: Alan Deidun), (B) *Fistularia commersonii* (photo: Puccio Distefano), (C) *Pterois volitans* (photo: Mariolina Corsini Foka and Gerasimos Kondylatos).

Ecology: Capable of inflating when threatened. Feeds on benthic invertebrates. It is a benthic species living above sandy substrate in the vicinity of the coral reef but also in deep waters up to 250 m.

Origin: Indian and Pacific Oceans.

First Mediterranean record: In 2003 from Turkey, in the Gökova Bay [96].

Distribution: Turkey, Israel, Rhodes, Greece, Tunisia, Crete.

Mode of introduction: Through the Suez Canal.

Impacts: It contains tetrodotoxin (TTX) that may cause death. It attacks fishes caught in nets and on lines and can cause serious damage to both fishing gear and catch.

Scientific name: *Pterois volitans* (Linnaeus, 1758) (Figure 4C).

Classification: Chordata (*Actinopterygii*, *Scorpaenidae*).

Common name: Red lionfish.

Description: It has greatly elongated dorsal-fin spines and a long pectoral fin. Head and body cream coloured to red to reddish-brown vertical stripes. Eight small white spots are present on the lateral line. It has often large tentacles above eyes.

Ecology: It inhabits natural and artificial substrates. It is a voracious predator feeding on small fish, shrimps and crabs. Lionfishes are well known for their venomous spines to ward off predators.

Origin: Indo-Pacific and Atlantic Ocean.

First Mediterranean record: In 2016 from Turkey, Iskenderun Bay [97].

Distribution: Turkey.

Mode of introduction: Through the Suez Canal.

Impacts: Is an invasive mesopredator that voraciously consumes native coral-reef fishes.

8. Managing and prevention strategies

Globalization of trade and travel, together with climate change, habitat modification, aquaculture and mariculture, the aquarium trade and biological invasions themselves have facilitated the introduction and spread of marine invasive species, and without an effort to manage such introductions, the number of invasive species is expected to become much greater in the future. Since invasive species are globally recognized as a threat, policies to reduce the introduction and spread of alien species, and to manage those species whose populations are already established, are a priority for governments within Europe, and for the European Union [98, 99]. Currently, several policies and legal instruments concern the introduction and

spread of potentially invasive species: for example, the convention on biological diversity (CBD), the Habitats Directive (Directive 92/43/EEC), the European Union marine strategy framework directive (MSFD), the ecosystem approach (EcAp) within UNEP-MAP's Barcelona Convention, the Biodiversity Strategy and the Regulation on the Prevention and Management of the Introduction and Spread of invasive alien species [100].

For a better understanding of the invasive potential and spread dynamics of invasive species, the establishment of regular monitoring programs is necessary. Moreover, public awareness campaigns, citizen science initiatives and conventional scientific surveys by scientists are fundamental to monitor invasive species and to manage continuous spill-over effects, especially in the areas most vulnerable to marine biological invasions (e.g. MPAs).

Invasive species can be managed through different strategies: prevention, early detection, eradication and control (The European Commission, [101]). Because biological invasions are generally irreversible, prevention is an important task in many management strategies [102]. It is the cheapest and most effective option to reduce the future ecological and economic costs of invasive species [103]. To prevent marine bioinvasions, one should focus first on the invasion pathway/vector in order to minimize the risks of further introductions [104]. Identification of the most common pathways for introduction can help mould international policies aimed at preventing this phenomenon. Since commercial shipping seems to be the most significant vector for exotic species introduction (through ballast water, hull fouling and passive dispersal through canals), ballast water and fouling management practices (e.g. installation onto all carrier ships of ballast treatment technology) have a pivotal role to play, but these will invariably increase the cost of shipped goods. The recent expansion of the Suez Canal has spurred the biological community to raise the alarm on the ecological implications of such an expansion [105], with this alarm enjoying unprecedented media attention within high-profile portals, including *The Guardian* and *The Economist*. Mitigation measures proposed by the biological community in an attempt to check the unremitting introduction of allochthonous species through the Suez Canal into the Mediterranean include the installation of salinity barriers and of air bubble screens.

Controlling the spread of invasive species requires international cooperation, and this is often difficult to achieve [106]. An important step towards prescribing the management of ballast water was achieved through the adoption by the International Maritime Organisation (IMO) of the International Convention for the Control and Management of Ships Ballast Water and Sediments (BWM Convention) in 2004, which will finally come on stream in September 2017 after enough signatory parties ratified it. With respect to hull-fouling management, anti-fouling practices are largely based on the application of biocides, toxic to biofouling organisms [107], but also with a broader ecological impact on the aquatic environment. As conventional and more aggressive anti-fouling alternatives, for example, those based on TBT, tributyltin, are phased out, there is a real concern that the rate of introductions of marine alien species via hull fouling could increase in future, until other effective anti-fouling systems are developed.

Aquaculture and mariculture practices can be more effectively controlled than any other pathway [108]. The FAO Code [109] discourages the use of invasive alien species in aquaculture

and requests consultation with neighbouring states before introducing alien species. In terms of aquaculture imports, quarantine measures have been recommended [110, 111]. The international aquarium trade represents a multi-billion dollar industry that has expanded rapidly since the 1970s [112]. Many species are incidentally imported as contaminants, along with intentionally introduced species [44], whilst intentional releases into the wild by aquarium hobbyists in the Mediterranean are not known (e.g. *Lutjanus sebae*—[113]). The aquarium trade could be regulated following similar procedures as to aquaculture and by raising awareness of the public about the dangers of releasing aquarium species to the sea.

To mitigate the ecological impacts of IAS in the Mediterranean, different actions can be undertaken: eradication (manual, biological and chemical methods), containment and control. Invasive species are successfully eliminated when actions start as soon as possible after their introduction [114]. Once an alien species become established in a non-native area, the implementation of effective control and mitigation strategies are next to impossible. Early detection of alien invasive species, together with the capacity to take rapid action, is the key to successful and cost-effective eradications.

An obstacle to a rapid, early-stage eradication by authorities is a lack of biogeographical information about the species in question. Therefore, a collaboration between researchers, resource management agencies, and policy makers is needed to make management procedures more effective. Since the evaluation of management measures is essential for appropriate actions [103], a set of criteria (effectiveness, ecological impact and impact on human health) have been recently proposed to evaluate the effectiveness of the same measures [115].

The complexity of interactions between native and invasive species and the associated impacts makes environmental management quite difficult [53]. Therefore, continuous research is fundamental to predict future invasions and their effects. Such research efforts, however, should also be directed towards informing stakeholders and assessing the effectiveness of different management measures to reduce invasions and their impacts [66]. A dire need for environmental auditing methodologies (e.g. CBA, DPSIR) applied to biological invasions and potential mitigation measures exists, as well as for high-quality information on the introduced species, for example, life histories, invasive strategies and impacts on ecosystem services and biodiversity. Moreover, the quantification and mapping of impacts, for example, through the ecosystem services approach, might greatly assist managers and policy makers in their decisions on prevention or mitigation actions to be taken [53].

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