Estuaries and coasts : Journal of the Estuarine Research Federation
2023, Volume 46, Pages 2190-2207
https://doi.org/10.1007/s12237-023-01188-9
https://archimer.ifremer.fr/doc/00828/93983/

A review of knowledge on the impacts of multiple anthropogenic pressures on the soft-bottom benthic ecosystem in Mediterranean coastal lagoons

Lacoste Elise [1,*], Jones Auriane [1], Callier Myriam [2], Klein Judith [3], Lagarde Franck [1], Derolez Valerie [1]

[1] MARBEC, Univ Montpellier, CNRS, Ifremer, IRD, Sète, France
[2] MARBEC, Univ Montpellier, CNRS, Ifremer, IRD, Palavas, France
[3] MARBEC, Univ Montpellier, CNRS, Ifremer, IRD, Montpellier, France

* Corresponding author : Elise Lacoste, email address : elise.lacoste@ifremer.fr

Abstract :

Mediterranean coastal lagoons provide important ecological functions and nature's contribution to people, but they are particularly vulnerable to multiple pressures due to their location at the land-sea interface and the many activities they host. Numerous research and monitoring programs have been conducted to study the functioning of Mediterranean coastal lagoons and to improve their ecological and chemical status, especially since the 2000s with the EU Water Framework Directive. However, many coastal lagoons still had not achieved a good ecological status by 2018. The soft-bottom benthic ecosystem plays a crucial role in the functioning of shallow coastal lagoons, regulating among others nutrient and oxygen fluxes, and hosting a high biodiversity. The alteration of this compartment by anthropogenic pressures is therefore a major problem. Through a literature review, this paper aims to summarize information available on the impacts of the five main human-induced pressures — i.e. exploitation of natural resources, habitat destruction, climate change, pollution and alien invasive species — on the soft-bottom benthic ecosystem in Mediterranean coastal lagoons (period 2000—2022), and to identify perspectives for future research that can contribute to the improvement of monitoring programs. Our review shows that resource exploitation and nutrient pollution have been the two most studied pressures whereas research is still underdeveloped on the impacts of climate change, invasive alien species, and contaminants of emerging concern. We also found that the recording and quantification of pressures is still poor, and that their cumulative effect is poorly understood. In terms of indicators, the microbial and microphytobenthic compartments are being overlooked and functional approaches could be strengthened. This review could help scientists realign research on pressures of priority interest and thus better assist stakeholders in managing coastal lagoons in times of global change

Keywords : : Biodiversity loss, Eutrophication, Pollution, Habitat destruction, Climate change, Resource exploitation, Alien invasive species

1. Introduction

There are about 400 coastal lagoons in the Mediterranean, mainly distributed in Italy, Greece, Turkey and France (Cataudella et al. 2015). These highly productive ecosystems ensure major ecological functions (e.g. regulation of matter cycles, biodiversity maintenance), provide valuable nature's contribution to people (Newton et al. 2018; Pérez-Ruzafa et al. 2019) and in many regions, are the focus of socio-economic interests and support regional economies (Newton et al. 2018). However, the high residence time of lagoon waters, fluctuating environmental conditions, and the multiple activities taking place in and near coastal lagoons make them particularly exposed and vulnerable to anthropogenic pressures (Viaroli et al. 2008; Zaldívar et al. 2008; Pérez-Ruzafa et al. 2019), with eutrophication considered for a long time as the main threat (de Jonge and Elliott 2001; Newton et al. 2014). Eutrophication is a naturally occurring process in most lagoons because they function as a sink for nutrient inputs from the sea and the land. However, excessive nutrient loads in catchment areas since the 1960s has resulted in rates of primary production exceeding rates of mineralization, leading to organic matter accumulation and recurrent and persistent periods of oxygen deficiency (Cloern 2001). These "dystrophic crises" promote nutrient fluxes from the sediment to the water column (Rysgaard et al. 1996; Souchu et al. 1998), which can be associated with the release of toxic compounds such as sulfide (Caumette and Baleux 1980; Castel et al. 1996), and result in mass mortality of benthic macrofauna and fish (Stachowitsch 1992). This issue has been the subject of several research programs in the 1980s and 1990s both at the European scale (e.g. CLEAN: Coastal lagoons and anaerobic processes (Caumette et al. 1996), ROBUST: The ROle of BUffering capacities in STabilising coastal lagoon ecosystems (de Wit et al. 2001), EUMAC: Eutrophication and benthic Macrophytes (Schramm 1999)) and at the regional scale (e.g. Trousselier and Deslous-Paoli 2001), which have laid the foundation for understanding, among others, the prominent role of the benthic ecosystem in the trophic functioning of coastal lagoons. These studies have also served as a reference for the establishment of various monitoring programs such as the European Water Framework Directive (WFD). This management plan was implemented in the 2000s in Europe to achieve the good ecological and chemical status of water bodies, mainly degraded by pollution from urban waste water and agriculture causing eutrophication. This has led to significant efforts to reduce nutrient inputs into water bodies categorized as ”transitional waters” by the WFD, allowing the progressive restoration of several coastal lagoons (Le Fur 2018; Derolez et al. 2020). Nonetheless, 60% of transitional waters had still not achieved a good or high ecological status by 2018, especially in Italy (Kristensen et al. 2018).

In addition to eutrophication, multiple anthropogenic pressures have emerged, including those associated with climate change such as warming, acidification or hypersalinization. The Millennium Ecosystem Assessment (MEA 2005), and more recently the Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services (IPBES 2019), defined five main human-induced drivers – also referred to as pressures – that directly and unequivocally influence ecosystem biodiversity and associated nature’s contribution to people: overexploitation of natural resources, habitat destruction, human-driven climate change, pollution (i.e. macropollutants related to eutrophication and micropollutants related to chemical contaminants) and invasive alien species. These pressures have been identified as the main threats in the Mediterranean Sea (Coll et al. 2010) and for semi-enclosed coastal systems in Europe (Newton et al. 2014), and their importance is increasingly recognized in the WFD (Cardoso and Free 2008; von der Ohe et al. 2011; Quevauviller 2011). In Europe, although many assessment methods have been developed and intercalibrated, not all pressures have been addressed and indicators cannot, in most cases, diagnose the cause(s) of coastal lagoon ecological degradation (Poikane et al. 2020). The same observation applies to North Africa for which information is diffuse and heterogeneous (El Mahrad et al. 2020). Consequently, better understanding the underlying drivers of Mediterranean coastal lagoons degradation is crucial if we are to manage these ecosystems more effectively.

In this review, we start by summarizing information available in the scientific literature (period 2000-2022) on the impacts of the five aforementioned anthropogenic pressures on the soft-bottom benthic compartment (Fig. 1). We chose this compartment because it is an excellent model for understanding changes in community structure and functioning (e.g. Pearson and Rosenberg 1978; Rhoads et al. 1978), and it plays a crucial role in the restoration trajectories of coastal lagoons (Ouisse et al. 2013, 2014). The literature was retrieved from two search platforms: Web of Science and Google Scholar. The search was first restricted by the topic "Mediterranean lagoon* AND benth* AND impact*", enriched by forward and backward citation tracking. The search was then enriched by looking for studies that addressed each of the five pressures listed above (e.g. "Mediterranean lagoon* AND benth* AND climate change"). We identified papers in which the intent was to analyze the direct impact on the state and/or functioning of any element of the benthic compartment (excluding ichthyofauna). A total of 93 studies were finally retained to build our narrative review (Table 1 and Table S1). On this basis, we then discuss research gaps and how management should realign with multiple pressures in times of global change.

2. Literature review on the impacts of five anthropogenic pressures on the soft-bottom ecosystem of Mediterranean Coastal lagoons

2.1. Habitat destruction

Mediterranean coastal lagoons are threatened by engineering works that mainly involve land claim and sand filling for coastal uses (e.g. ports, marinas, urbanizations), bottom dredging for sand extraction, channel creation or beach conditioning, and inlet enlargement or closure to control lagoon-sea exchanges (Pérez-Ruzafa et al. 2019). These engineering works can alter geomorphology, sediment transport, seafloor integrity and hydrodynamics and lead to habitat loss (Newton et al. 2014). Specifically, dredging may cause many negative effects on the benthic compartment, according to Quigley and Hall (1999) and Miller et al. (2002), mainly by 1/ changing sediment property, 2/ re-suspending fine sediment and releasing porewater, which can lead to nutrient and/or contaminant pollution and to hypoxic events, 3/ reducing benthic macrofauna richness and abundance, including sometimes complete community loss.

Among the publications retrieved concerning habitat destruction and its impacts on the soft-bottom benthic compartment of Mediterranean coastal lagoons (Table 1), most of the pressures corresponded to dredging and took place in Italian or Tunisian lagoons (Ponti et al. 2009; Khedhri et al. 2015, 2016, 2017). Two publications focused on dredged sediment disposal (Munari and Mistri 2014; Bettoso et al. 2020) and one on lagoon-sea water exchange reduction (Como et al. 2007). The impacts of dredging on soft-bottom macrofauna community were limited in space, showing a decrease in species diversity along with an increase of the abundance of some species (*Streblospio shrubsolii* and *Corophium insidiosum)* (Ponti et al. 2009), or changes in the trophic structure (Khedri et al. 2015).

Three publications used the BACI approach (Before/After Control/impact), authorizing a robust comparison of sampling sites (Bettoso et al. 2020; Munari and Mistri 2014; Ponti et al. 2009). Five publications used benthic descriptors to assess the impact of habitat destruction on macrofauna (Table S1), based on trophic groups and on indices calculated for WFD diagnoses (AMBI, BENTIX, M-AMBI, TUBI, BITS) (Munari and Mistri 2014; Khedhri et al. 2015, 2016, 2017; Bettoso et al. 2020). Out of these five publications, only two included yearly monitoring (Table S1), and showed significant negative impacts of habitat modifications on macrofauna taxonomic diversity and ecological indices, which had recovered in a year or less (3-6 months (Bettoso et al. 2020) and 1 year (Munari and Mistri 2014)).

All the articles focused on sediment properties or on macrofauna communities, but never investigated other biotic compartments like macrophytes, or considered more functional approaches like food web structure or carbon, nutrient and oxygen fluxes. Finally, we did not find studies illustrating the impacts of port or marina construction on the benthic compartment although it was highlighted as an important pressure on Mediterranean coastal lagoons (Newton et al. 2014; Pérez-Ruzafa et al. 2019; El Mahrad et al. 2020).

2.2. Pollution

Eutrophication remains a major environmental issue, aggravated by the current trend of rising temperatures and more frequent torrential rains due to climate change. In the past few years, several studies have described drastic changes of the benthic compartment linked to eutrophication, such as changes in the distribution patterns of macrophytes (Le Fur et al. 2018) or reduction in macrofauna richness and diversity (Jones et al. 2022 PREPRINT) at the scale of French Mediterranean lagoons. Other studies focused on the effects associated, in particular recurrent and persistent periods of hypoxia and anoxia - known as dystrophic crises - which include the modification of oxygen and nutrient fluxes at the sediment-water interface (Zilius et al. 2015; Rigaud et al. 2021), seagrass mortality (Viaroli et al. 2008), and changes in macrofauna community structure (Dolbeth et al. 2003) with death of organisms like *Polydora ciliata* (Como and Magni 2009) or *Ruditapes philippinarum* (Mahé et al. 2021). Eutrophication may also modify food web structure and functioning as shown by Carlier et al. (2009a) who observed marked differences in $\delta^{13}C$ and $\delta^{15}N$ of food sources and consumers between the lagoons of Canet and La Palme in France. Following the implementation of the WFD and the reduction of urban nutrient inputs, several studies described the restoration trajectories taking place in coastal lagoons, also referred to as oligotrophication, with an apparently strong hysteresis (Pasqualini et al. 2017; Le Fur 2018; De Wit et al. 2020). Recovery trajectory of the macrophyte community in 21 French Mediterranean coastal lagoons occurred with regime shifts, and a full recovery from highly eutrophic to oligotrophic conditions may require more than a decade (Le Fur et al. 2019). More generally, the full recovery of coastal and estuarine benthic ecosystems from long-term degradation can take a minimum of 15-25 years (Borja et al. 2010).

Other common pollutions (i.e. micropollutions) reported for Mediterranean coastal lagoons are trace metals from mining and industrial activities (e.g. Marín-Guirao et al. 2005; Ruiz et al. 2012; Martins et al. 2016), and historical contaminants such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and organochlorinated pesticides (OCPs) from industrial and agricultural effluents (e.g. Cibic et al. 2012; León et al. 2017; Ben Salem et al. 2019). All these pollutants are mainly brought by rivers, meaning that flash flood events may have a significant impact on sediment contamination (León et al. 2017; Moreno-González and León 2017). These pollutions have a significant impact on benthic species such as the mussel *Mytilus galloprovincialis* (Barhoumi et al. 2014) or the clam *R. philippinarum* (Carafa et al. 2007) which both show high bioaccumulation rates. The seagrass *Cymodocea nodosa* and the seaweed *Ulva rigida* have also been shown to accumulate trace metals and herbicides (Marín-Guirao et al. 2005; Carafa et al. 2007), and the occurrence of abnormalities in foraminiferal tests has been correlated to trace metal pollution (Coccioni et al. 2009). At a higher level of biological organization, pollution affects the composition and distribution of benthic communities. The abundance of tolerant species such as the foraminifera *Quinqueloculina bicostata* has been shown to increase in association with metal pollution (Foster et al. 2012), and the bacterial community composition has been linked with PAHs concentration in the Bizerte lagoon (Ben Salem et al. 2019). Macrofauna, characterized by univariate diversity indices (e.g. species richness, Shannon) or by the biotic indices AMBI and M-AMBI, showed a weak response to chemical contamination (Marin-Guirao et al. 2005; Pitacco et al. 2020) while herbicides and trace metals may have played a role in the decline of seagrass beds observed in a French lagoon (Espel et al. 2019). Finally, our review reveals the lack of studies on the ecosystem level effect of pollution (both macro- and micro-pollution). We found only 3 studies that investigated the effect of micropollution on functional processes. In an integrated study, no taxonomic but functional differences of microbial communities was shown along a gradient of hydrocarbon pollution in a riverine lagoonal system where contaminated sediment hosted an extremely active microbial community compared with unpolluted sites (Cibic et al. 2012). Conversely, an inhibition of microbial processes (as a proxy of ecosystem functioning) was observed along a gradient of contamination in the Mar Piccolo of Taranto (Franzo et al. 2016). Another study took a first step in studying ecosystem functionality through biological trait analysis of polychaetes associated with contamination (Nasi et al. 2018). This finding of a lack of functional approach is in line with a recent French national expert report that highlights the lack of studies on the effects of pesticides in the marine environment at the ecosystem level (Leenhardt et al. 2022).

2.3. Exploitation

Over the last 20 years (28 reviewed papers, Table 1), the effects of aquaculture on benthic ecosystems were studied in different Mediterranean coastal lagoons in Italy (Venice, Marinetta and Sacca di Goro), in France (Thau and Salses Leucate) or in Tunisia (Bizerte). Among these lagoons, some are particularly exploited, such as Thau with 20% of the surface dedicated to oyster and mussel production (*Magallana gigas*, 6 110 T/year ; *Mytilus galloprovincialis*, 2 385 T/ year in 2019), and Sacca di Goro with 35% of the surface exploited for clam production (*Ruditapes philipinarum*, 6 000 T/year). Shellfish farming may affect lagoon benthic ecosystems through different processes that have been extensively reviewed worldwide (Gallardi 2014; Lacoste and Gaertner-Mazouni 2015; Lacoste et al. 2020; Boudouresque et al. 2020).

In Mediterranean coastal lagoons, several studies showed impacts of aquaculture on physical processes (e.g., sedimentation, erosion) and sediment composition. This has been particularly studied in the Venice lagoon, where intensive harvesting of the non-native bivalve Manila clam *R. philippinarum* has resulted in the loss of fine sediment through resuspension (Pranovi et al. 1998, 2004).The increase in resuspension of the top layer of sediment caused by the mechanical harvesting of clam (locally known as the "rusca" method) has been shown to bring the anoxic layer close to the bottom, with potential impacts on biogeochemical cycles and on the short-term recolonization by benthic organisms (Badino et al. 2004). Sfriso et al. (2005) confirmed that clam harvesting has significantly contributed to increase sediment resuspension and homogenize surface sediment granulometry and dry density.

A second group of studies showed impacts of aquaculture on benthic organisms at the individual level (e.g. physiological performance of *R. philippinarum*, Moschino et al. 2011), but the majority revealed contrasting results regarding the effects at the community level, focusing either on meiofauna (Mahmoudi et al. 2008; Lacoste et al. 2020), macrofauna (Castaldelli et al. 2003; Mantovani et al. 2006; Duport et al. 2007; Lacoste et al. 2020, 2022) or macrophytes such as seagrass meadows (*Cymodocea nodosa*, *Zostera* spp., Boudouresque et al. 2020). In Bizerta lagoon, mussel biodeposition led to modifications of the abundance and diversity of free-living nematodes that could lead to food limitation for their predators and ultimately alter the entire benthic community and ecosystem (Mahmoudi et al. 2008). Conversely, little or no effect of clam harvesting has been detected on macrofauna taxonomic and functional composition (Castaldelli et al. 2003; Mantovani et al. 2006). No impact of shellfish farming has been shown on isotopic values of macrofauna (Carlier et al. 2009b).

Finally, many studies looked at the effect of shellfish farming on ecosystem functioning. A majority of studies determined spatial and/or temporal variations of biogeochemical fluxes at the sediment water interface, including measures of the vertical distribution of oxygen and of oxygen fluxes (e.g. Viaroli et al. 2003; Nizzoli et al. 2005; Dedieu et al. 2007), CO_2 fluxes (Bartoli et al. 2001), $CaCO_3$ and CO_2 production/sequestration (Mistri and Munari 2012), nitrogen and phosphorus fluxes (e.g. Bartoli et al. 2001; Nizzoli et al. 2005; Lacoste et al. 2022), phosphorus diagenesis (Anschutz et al. 2007), vertical distributions of dissolved sodium, potassium, magnesium, calcium (Metzger et al. 2007), acid volatile sulphide, chromium reducible sulphur and labile amorphous iron (Viaroli et al. 2003). Mussel farming and bottom clam culture may create "hotspots" of nutrient fluxes with annual N and P regeneration rates being 4.9 and 13.5 (mussel) and 4.5 and 14.9 (clams) fold greater than those of unfarmed control sediments (Nizzoli et al. 2011). Finally, Schmidt et al. (2007) showed the importance of oysters biodeposition on bioturbation in the Thau lagoon.

2.4. Invasive alien species

Coastal lagoons are considered to be key entry points for the arrival of new alien species in the Mediterranean Sea, with the Venice and Thau lagoons as prime examples (Boudouresque et al. 2010; Marchini et al. 2015). Indeed, coastal lagoons are often home to important cultures of non-native shellfish species (e.g. *M. gigas, R. philippinarum*). For example, the import of non-native oysters (seed and older individuals) has in many cases served as a vector for other alien species, mainly their epibiota and parasites, such as macroalgae (e.g. *Undaria pinnatifida*) and invertebrates (e.g. *Myicola ostreae*), which in turn have the potential of becoming invasive (Marchini et al. 2015). Furthermore, shipping traffic of commercial ships and recreational boats, another potential vector for alien species invasion, is intense close to and inside coastal lagoons.

Despite the numerous alien species recorded in Mediterranean coastal lagoons (55 established alien species in Venice lagoon by 2014 (Marchini et al. 2015) and 50 alien macrophyte species by 2009 in the Thau lagoon (Boudouresque et al. 2010), their effect on the benthic compartment seems to have been neglected. Indeed, our literature survey identified only 14 articles, for the considered period, that investigated the effect of alien species on soft-bottom benthic organisms and/or benthic ecosystem functioning, or that summarized older literature on the subject (Sfriso et al. 2020; Streftaris and Zenetos 2006). Only one study investigated the effect of invasive alien species on the sediment structure of lagoons and recorded no significant effect of the mussel *Arcuatula senhousia* on sediment features in the Oristano lagoon-gulf system (Western Sardinia) (Como et al. 2018). As far as benthic assemblage structure and composition was concerned, other studies focused on the effect of invasive alien macroinvertebrate on macrofauna diversity, or of invasive alien macrophyte on macrophyte diversity with just one investigating the effect of an invasive alien macrophyte on macrofauna (Nonnis Marzano et al. 2003). Sampling designs employed were largely spatial comparisons (control *vs* impact) and only a few took into account time (pre-invasion *vs* post-invasion) (Table S1). Overall, all except one reported significant changes in community composition with four also reporting changes in community structure (taxonomic distinctiveness, richness, and evenness) (Pranovi et al. 2006; Streftaris and Zenetos 2006; Munari 2008; Sfriso et al. 2012). Most studies were conducted in Italian lagoons and dealt with the following invasive alien species: the tube-building worm *Ficopomatus enigmaticus* (Lesina lagoon, Italy, Nonnis Marzano et al. 2003), the bivalve *Anadara inaequivalvis* (Venice lagoon, Ambrogi 2000), the Asian mussel *A. senhousia* (Sacca di Goro lagoon, Mistri 2003; Munari 2008), the pearl oyster *Pinctada radiata* (Bizerte lagoon, Tlig-Zouari et al. 2011), the Manila clam *R. philippinarum* (Venice lagoon, Pranovi et al. 2006), the macroalgae *Agarophyton vermiculophyllum* (lagoons of Sacca di Goro and Pialassa della Baiona, Sfriso et al. 2012) and *Valonia aegagropila* (Lesina lagoon, Nonnis Marzano et al. 2003).

In terms of functional approaches, few studies investigated the effect of invasive alien species on trophic interactions and only three species have been considered: the mussel *A. senhousia*

(Como et al. 2018), the blue crab *Callinectes sapidus* (Mancinelli et al. 2013; Carrozzo et al. 2014; Mancinelli et al. 2017) and the ctenophore *Mnemiopsis leidyi* (Marchessaux et al. 2021a,b). Five out of six studies revealed significant effects of invasive alien species on benthic communities through trophic competition and predation by using bulk carbon and nitrogen stable isotopes and gut content analyses (Mancinelli et al. 2013; Carrozzo et al. 2014; Mancinelli et al. 2017; Marchessaux et al. 2021a,b). On the level of ecosystem functioning, six studies found effects of invasive species on benthic-pelagic coupling and anoxia or suspected such effects. Between 1990 and 1999, the spread of the benthic Manila clam *R. philippinarum* changed the functioning of the Venice lagoon due to its relatively high clearance rate which greatly increased the macrobenthic filtration capacity (Pranovi et al. 2006). In the Berre lagoon (South of France), the pelagic ctenophore *M. leidyi*, which preys on benthic organisms probably plays an underestimated role in the transfer of benthic organic matter into the pelagic food web (Marchessaux et al. 2021a,b). Lastly, the invasive macrophyte species *Laminaria japonica* in the Thau lagoon (Streftaris and Zenetos 2006) and *V. aegagropila* in the Lesina lagoon (Nonnis Marzano et al. 2003) were both reported to cause local anoxia whereas *A. vermiculophyllum* decreased the risk of summer anoxia in the Venice lagoon (Sfriso et al. 2020).

2.5. Climate change

The scientific literature dealing with the effect of climate change on the soft-bottom benthic compartment in Mediterranean coastal lagoons is poor (9 studies found, Table 1), despite these ecosystems being considered to be particularly vulnerable to such change and its effects (Lloret et al. 2008). Among the expected hydroclimatic changes, high summer temperatures associated with rainfall – that influence salinity and nutrient level through river discharge – appear to be the main driving force behind anoxia processes. In the Thau lagoon, anoxic crises in the last 50 years have been shown to be mainly triggered by eutrophic status and higher summer temperatures, and to a lesser extent by lower wind speeds and higher precipitations in summer (Derolez et al. 2020), a phenomenon which is amplified during high North Atlantic Oscillation index and warm positive phase of El Niño Southern Oscillation (Harzallah and Chapelle 2002). Prolonged dry periods associated with high temperature and low oxygen solubility deeply alter benthic nutrient recycling in coastal lagoons, favoring nitrogen regeneration and algal blooms (Magri et al. 2020). During these periods, increasing salinity due to evaporation and reduced freshwater inputs can exacerbate the effects of anoxia, by reducing oxygen saturation and stimulating sulphide formation.

The increasing frequency and intensity of summer thermal anomalies associated with hypersalinity, and the potentially associated anoxic crises are likely to become a major threat to macrobenthic communities in transitional environments (Pitacco et al. 2018; Mercurio et al. 2021). For example, the 2003 summer heatwave in the Comacchio saltworks (Italy) reduced the species richness of the macrofauna community which shifted from mollusc- to annelida-dominated (Munari 2011; Pitacco et al. 2018). Exploited natural resources such as the Manila clam *R. philippinarum* could also be impacted by climate change with consequences for the sustainability of aquaculture (Canu et al. 2010; Ghezzo et al. 2018).

Finally, climate change might also play a role in the coastal eutrophication process as illustrated by the study of Lloret et al. (2008). In the Mar Menor lagoon that they studied, the enormous biomass of *Caulerpa prolifera* maintains water clarity and enhances lagoon resistance to phytoplankton blooms. Through an experimental study, they highlighted that the expected decrease in the amount of light reaching the bottom – due to increased sea-level rise, nutrient inputs and suspended solid runoffs – could lead to a progressive disappearance of macrophytes and thus an alteration of the trophic status of the system.

2.6. Cumulative pressures

While pressures may occur in isolation, 97.7% of the ocean is currently affected by more than one pressure (Halpern et al. 2015), and coastal regions have been shown to be the most threatened by cumulative pressures in the Mediterranean (Coll et al. 2010; Micheli et al. 2013; Korpinen et al. 2021). In many studies however, only the presence or absence of a unique driver is considered whereas cumulative impacts are increasingly obvious, as it is the case for eutrophication and climatic extreme events. In a lab experiment simulating the Mar Menor lagoon conditions, warming and nitrogen:phosporus ratio (whose level depends on inputs from the watershed and internal regeneration) have been shown to modify the population of an epiphytic diatom (Belando et al. 2019). Still in the Mar Menor, the progressive increase in nutrient loads and resulting algal blooms, combined with an extreme rainfall event, led to the complete extinction of the bivalve *Pina nobilis* in the deeper part of the lagoon (Nebot-Colomer et al. 2021). Changes in the local environmental conditions may also have favored the intrusion of a new pathogen, adding extra pressure on the already weakened population of *P. nobilis* (Nebot-Colomer et al. 2021). In the Lesina lagoon, an artificial change in the hydrological regime (temporary closure of a tidal channel) combined with unusual meteorological parameters has been shown to cause a dystrophic crisis, accompanied by a shift from a macrophyte-based system to a phytoplankton-based system in the isolated area (Vignes et al. 2009). Finally, in conjunction with new pathogens and/or chemicals, the increasing frequency of extreme meteorological events in the Mediterranean region (Kysely et al. 2012; Cramer et al. 2018) could also cause climate-induced toxicant sensitivity responses in some species, as shown for the bivalves *R. philippinarum* and *Mytilus galloprovincialis* exposed to caffeine and heatwaves (De Marchi et al. 2022).

Overall, with only a few studies to date focusing on cumulative impacts in the marine realm, which showed idiosyncratic responses (Gissi et al. 2021), it appears that the nature of the interactions between pressures is largely unpredictable (Côté et al. 2016; Carrier-Belleau et al. 2021), and that further work should be encouraged to enable general conclusions to be drawn.

3. Perspectives for future research and monitoring programs on soft-bottom benthic ecosystem in Mediterranean coastal lagoons

3.1. Realign research with pressures of emerging concern

Among the studies reviewed, exploitation and pollution have been the two most studied human-induced pressures in Mediterranean coastal lagoons so far (Table 1, Fig. 2). Eutrophication has been the focus of much research since the 1980s, complemented in the 2000s by regulatory monitoring of European ecosystems through the WFD. Compared to this, the emerging pressures formalized in the 2000s by the MEA suffer from a lack of research as illustrated by the small number of studies identified in our review concerning climate change (Table 1). Worldwide, the impact of extreme events on benthic communities in coastal lagoons has been the focus of less than 40 studies (Durreau et al. 2021). Ecosystem monitoring and management is therefore focused on the provision of ecosystem functions and services under current environmental conditions, yet this could rapidly lead to inappropriate management guidance and undervaluation of the importance of human impacts on biodiversity. Research on biodiversity loss must therefore realign with emerging issues to match predicted impact severity and better guide management actions (Mazor et al. 2018). In addition to climate change, we call for further research on the issues of invasive alien species and contaminants of emerging concern. Our review emphasizes that although a lot of research has inventoried the presence of invasive alien species in Mediterranean coastal lagoons, the quantification of the role of these species on benthic biodiversity and ecosystem functioning is in its infancy. Functional impacts of invasive alien species on the environment they colonize are hard to qualify and quantify but efforts should be made in this domain to anticipate negative and cascading impacts at the ecosystem level (Dethier and Hacker 2004). As an example, the invasive benthic suspension feeder *Crepidula fornicata* has been shown to strongly influence important ecological processes such as the coastal ‘silicate pump’ or carbon cycling in the Bay of Brest (Ragueneau et al. 2005; Martin et al. 2007). As another priority, we identified the need to monitor the distribution and fate of newly-detected contaminants in sediments, as this compartment represents a major reservoir of pollution, and to better evaluate their impact at the community and ecosystem level. Contaminants of emerging concern such as antibiotics, sun creams and nano/microplastics are still overlooked at the moment despite being a particular issue in marine and transitional waters (e.g. Anbumani and Kakkar 2018; Fastelli and Renzi 2019; Renzi et al. 2020) where they are likely to be brought in significant amounts by aquaculture, shipping/sailing or other recreational activities. Although the research collected in our review shows that contaminants from diverse origins may have a significant impact on all the biological components of the sediment, most of them are still unregulated and the effects they can produce may be missed or overlooked in many monitoring and surveillance programs such as the WFD (Fig. 2).

For a comprehensive understanding of ecosystem modifications linked to anthropogenic pressures in Mediterranean coastal lagoons, a necessary step is to quantify the exposure of lagoons to the identified pressures more precisely and on a regular basis. A common framework for the description and quantification of the multiple anthropogenic pressures in Mediterranean coastal lagoons is lacking, and efforts remain fragmented, relying mainly on semi-quantitative assessments or expert judgments (Borja et al. 2011; Orfanidis et al. 2014). In the French Mediterranean, the quantification of multiple pressures for 25 coastal lagoons dates back to 2013 (Derolez et al. 2014). In Greece and North Africa, pressure quantification is only recently available for a few study sites (Maneas et al. 2019; Bray et al. 2022; El Kateb et al. 2018; El Mahrad 2020). Recent studies based on Geographic Information System analyses (Morant et al. 2021) assessing pollution and hydro-morphological pressures in coastal lagoons are promising and should be updated regularly and made available to stakeholders. Some initiatives could serve as a basis to facilitate data gathering by assembling, organizing and sharing environmental knowledge among the Mediterranean, like the open-data platform MEDTRIX (https://medtrix.fr/), which makes available results from the WFD monitoring and the contamination of French coastal waters.

3.2. Finding suitable indicators for monitoring to detect anthropogenic pressures

Today, when most assessment methods (i.e. indicators) in European transitional waters are reported to be responding to eutrophication or organic pollution, other pressures such as toxic pollution, hydro-morphological modifications or acidification received significantly less efforts (Poikane et al. 2020). More general concerns have been raised that not all pressures are addressed adequately by the assessment methods currently in use (Reyjol et al. 2014). Although Borja et al. (2011, 2015) have shown that several marine and estuarine benthic quality assessment indices, such as the M-AMBI for macrofauna, have significant correlations with human pressures (e.g. eutrophication, organic enrichment, harbours), other studies showed that these indices used in the WFD context have difficulties detecting pressures when applied in a generalized way across coastal lagoons (Munari and Mistri 2008; Simboura and Reizopoulou 2008; García-Sánchez et al. 2012; Jones et al. 2022 *preprint*). Basic scientific research is continuously needed to propose the use of new descriptors and develop smart and easy-to-use indicators that do not require high sampling and analytical efforts (Bonometto et al. 2022).

It also appears that the WFD is missing key components in the assessment of soft-bottom benthic ecosystems such as microbes, microphytobenthos and meiofauna (Fig. 2), whereas several studies showed their usefulness in detecting changes associated with human pressures. Although there are still some limitations in their routine use, nematodes (main group of meiofauna) provide elements to assess the ecological quality status of Mediterranean coastal ecosystems through specific indicators (Moreno et al. 2011; Semprucci et al. 2015). Collaborative work between African and European researchers to enrich sequence databases (DNA barcoding, NGS), in conjunction with morphotaxonomy (Boufahja et al. 2015), could be part of the solution to progress in the description of nematode diversity in the Mediterranean region and use them as models to evaluate lagoon ecosystem status in the face of global changes. Microbes (bacteria, archaea, and protists) are also seldom used as bioindicators in routine assessments (Table 1, Fig. 2) although they have been recognized for their importance in benthic diversity and functioning. Metagenomic and metatranscriptomic are promising tools that could help to predict community functional changes under different environmental and anthropogenic pressures. However, few works are currently available and further manipulative studies targeting the effects of individual and multiple pressures on aquatic microbial communities should be conducted to evaluate their possible integration in biomonitoring programs.

Most recent research emphasizes the importance of maintaining not only a high diversity of species, but also functional and evolutionary processes, for effective conservation and maintenance of ecosystems at different scales (Meyer et al. 2015; Isbell et al. 2017). This has recently motivated a lot of research on the relationships between macrobenthic biodiversity (or loss of biodiversity) and ecosystem functioning (Solan et al. 2004; Ieno et al. 2006), with a clear deficit in Mediterranean coastal waters (Lam-Gordillo et al. 2020). As shown by our literature review, there is a real lack of studies concerning the impacts of various anthropogenic pressures on the functional processes taking place in the soft sediments of coastal lagoons. Nonetheless, pollution such as microplastic has been shown to impair the health and behavior of some engineer species (the lugworm *Arenicola marina),* leading to a reduction of primary productivity in coastal sandy sediments (Green et al. 2016). Numerous studies exploring the relationships between organic load and oxygen and nutrient fluxes at the benthic interface in a context of aquaculture exploitation (Table 1) also showed significant impacts. Consequently, we can only encourage the use of biological trait analysis and functional diversity which are recognized as being more effective than species richness *per se* to describe links between biodiversity and metrics of ecosystem functioning (e.g. decomposition rates, nutrient uptake) (Gagic et al. 2015; Strong et al. 2015; Cernansky 2017). Such research efforts will allow a generalization of the use of functional indices (*stricto sensu,* Mason et al. 2005) in the evaluation of the benthic ecosystem response to pressures in coastal lagoon ecosystems.

3.3. Improve and harmonize sampling design in research and monitoring

Comparison of research studies dealing with environmental impacts in coastal lagoons is challenging due to the high spatio-temporal variability between lagoons and lack of homogeneous approaches (Table S1). The studies show contrasting results and differ across the lagoon studied, the identity and intensity of the pressures (e.g. contaminant levels, density of the invasive species), and the sampling design employed (spatial replication, temporal replication etc.). In most studies, and in particular for impact assessments, choosing appropriate controls is of paramount importance (Underwood 1994). In order to disentangle the effects of natural environmental change on benthic communities from the impacts of specific anthropogenic pressures, it is thus essential to combine temporal and spatial replication in well-designed experiments (e.g., Before-After Control-Impact (BACI)). To be able to draw general conclusions, there is a strong need for comparable experimental designs, long-term and large spatial scale (comparison of different lagoons) research efforts. The same applies to monitoring objectives. Whereas regulatory monitoring of benthic ecosystems is still not deployed in North African Mediterranean coastal lagoons (El Mahrad et al. 2020), in EU countries, WFD has led to the development of standardized monitoring programs. For the soft-bottom compartment, only macrophytes and macrofauna are regularly monitored through indicators (respectively EXCLAME and M-AMBI (EU, 2018)) to evaluate their ecological status, and sediment characteristics (granulometry and percentage of organic matter, carbon, and nitrogen) are surveyed as explanatory parameters (Fig. 2). Despite Ferreira et al. (2007) recommending seasonal to bi-annual sampling for the WFD monitoring of macrophytes and macroinvertebrates in transitional waters, these monitoring surveys are less frequent (twice a year to every 3-6 years) in European Mediterranean coastal lagoons (see Sfriso et al. 2009 and Le Fur et al. 2018 for macrophytes and Cabana et al. 2013 and Jones et al. 2022 *preprint* for macrofauna). The high natural variability and heterogeneity of transitional water systems are therefore not likely captured with these minimum sampling frequencies, even if the long-term datasets provided by these monitoring programs are highly valuable. Many river basin managers agree that change is needed in WFD monitoring to provide sufficient spatial and temporal resolution and in some cases to make it more cost-effective (Carvalho et al. 2019). In line with Carvalho et al. (2019), we thus recommend further WFD implementation guidance on strategic design of monitoring networks, to harmonize best practice in addressing these different issues.

Conclusion

The soft-bottom benthic compartment is crucial in the functioning of coastal lagoon ecosystems which have been the focus of much research since the 1980s in the eutrophication context. We reviewed the currently studied impacts of five major anthropogenic drivers of biodiversity loss on soft-bottom benthic ecosystems of Mediterranean lagoons, and identified uneven efforts to address them. Overall, the impacts of invasive alien species and emerging chemical contaminants are particularly overlooked, as well as the effects of climate change which may exacerbate the already existing pressures. The impacts in terms of ecosystem functioning were also weakly addressed. The long-term monitoring of water bodies implemented in e.g., the EU

WFD, has provided valuable information on the ecological status trajectories of many coastal lagoons. However, in the face of multiple and cumulative pressures, it is time to gain new knowledge and to reinforce monitoring programs to be sure to capture the complexity of the undergoing changes. Such effort is important because Mediterranean coastal lagoons are ecologically valuable and provide many nature's contributions to people.

Acknowledgements:

The authors thank the MARBEC-LER/LR researchers for the many fruitful discussions and the two reviewers for their valuable comments, which greatly helped to improve an earlier version of this article.

Bibliography

Accornero, A., R. Gnerre, and L. Manfra. 2008. Sediment concentrations of trace metals in the Berre lagoon (France): An assessment of contamination. *Archives of Environmental Contamination and Toxicology* 54: 372–385.

Ambrogi, A.O., 2000. Biotic invasions in a Mediterranean Lagoon. Biol Invasions 2, 165–176. https://doi.org/10.1023/A:1010004926405

Anbumani, S., and P. Kakkar. 2018. Ecotoxicological effects of microplastics on biota: a review. *Environmental Science and Pollution Research*. Springer.

Anschutz, P., G. Chaillou, and P. Lecroart. 2007. Phosphorus diagenesis in sediment of the Thau Lagoon. *Estuarine, Coastal and Shelf Science* 72: 447–456.

Arienzo, M., A. Masuccio, and L. Ferrara. 2013. Evaluation of sediment contamination by heavy metals, organochlorinated pesticides, and polycyclic aromatic hydrocarbons in the Berre coastal lagoon (Southeast France). *Archives of Environmental Contamination and Toxicology* 65: 396–406.

Badino, G., F. Bona, A. Maffiotti, O. Giovanardi, and F. Pranovi. 2004. Impact of mechanical clam harvesting on a benthic habitat: Evaluation by means of sediment profile imaging. *Aquatic Conservation: Marine and Freshwater Ecosystems* 14.

Barhoumi, B., A. Elbarhoumi, C. Clérandeau, A. M. Al-Rawabdeh, A. Atyaoui, S. Touil, M. R. Driss, and J. Cachot. 2016. Using an Integrated Approach to Assess the Sediment Quality of a Mediterranean Lagoon, the Bizerte Lagoon (Tunisia). *Ecotoxicology* 25. Springer New York LLC: 1082–1104.

Barhoumi, B., K. Le Menach, C. Clérandeau, W. Ben Ameur, H. Budzinski, M. R. Driss, and J. Ô. Cachot. 2014. Assessment of pollution in the Bizerte lagoon (Tunisia) by the combined use of chemical and biochemical markers in mussels, *Mytilus galloprovincialis*. *Marine Pollution Bulletin* 84: 379–390.

Bartoli, M., D. Nizzoli, P. Viaroli, E. Turolla, G. Castaldelli, E. A. Fano, and R. Rossi. 2001. Impact of *Tapes philippinarum* farming on nutrient dynamics and benthic respiration in the Sacca di Goro. *Hydrobiologia* 455: 203–212.

Belando, M. D., Martínez, P. M., Aboal, M. (2019). Interactive effects of warming and eutrophication on population dynamics and stalk production of epiphytic diatoms in transitional waters. Estuarine, Coastal and Shelf Science, 229(May), 106413. https://doi.org/10.1016/j.ecss.2019.106413

Bellucci, L. G., M. Frignani, D. Paolucci, and M. Ravanelli. 2002. Distribution of heavy metals in sediments of the Venice Lagoon: The role of the industrial area. *Science of the Total Environment* 295: 35–49.

Bettoso, N., I. F. Aleffi, L. Faresi, A. D’Aietti, and A. Acquavita. 2020. Macrozoobenthos monitoring in relation to dredged sediment disposal: The case of the Marano and Grado Lagoon (northern Adriatic Sea, Italy). *Regional Studies in Marine Science* 33: 100916.

Bonometto, A., E. Ponis, F. Cacciatore, E. Riccardi, S. Pigozzi, P. Parati, M. Novello, et al. 2022. A New Multi-Index Method for the Eutrophication Assessment in Transitional Waters: Large-Scale Implementation in Italian Lagoons. *Environments - MDPI* 9.

Borja, Á., D. M. Dauer, M. Elliott, and C. A. Simenstad. 2010. Medium- and Long-term Recovery of Estuarine and Coastal Ecosystems: Patterns, Rates and Restoration Effectiveness. *Estuaries and Coasts* 33: 1249–1260.

Borja, A., Barbone, E., Basset, A., Borgersen, G., Brkljacic, M., Elliott, M., Garmendia, J.M., Marques, J.C., Mazik, K., Muxika, I., Neto, J.M., Norling, K., Rodríguez, J.G., Rosati, I., Rygg, B., Teixeira, H., Trayanova, A., 2011. Response of single benthic metrics and multi-metric methods to anthropogenic pressure gradients, in five distinct European coastal and transitional ecosystems. Mar Pollut Bull 62, 499–513. https://doi.org/10.1016/j.marpolbul.2010.12.009

Borja, Á., S. L. Marín, I. Muxika, L. Pino, and J. G. Rodríguez. 2015. Is there a possibility of ranking benthic quality assessment indices to select the most responsive to different human pressures? *Marine Pollution Bulletin* 97: 85–94.

Boudouresque, Charles F., J. Klein, S. Ruitton, and M. Verlaque. 2010. Biological Invasion: The Thau Lagoon, a Japanese Biological Island in the Mediterranean Sea. In *Global Change: Mankind-Marine Environment Interactions*, ed. H.-J. Ceccaldi, I. Dekeyser, M. Girault, and G. Stora, 151–156. Springer Netherlands.

Boudouresque, Charles François, A. Blanfuné, G. Pergent, C. Pergent-Martini, M. Perret-Boudouresque, and T. Thibaut. 2020. Impacts of Marine and Lagoon Aquaculture on Macrophytes in Mediterranean Benthic Ecosystems. *Frontiers in Marine Science* 7: 1–19.

Boufahja, F., F. Semprucci, H. Beyrem, and P. Bhadury. 2015. Marine Nematode Taxonomy in Africa : Promising Prospects Against Scarcity of Information. *Journal of Nematology* 47: 198–206.

Bray, L., S. Faulwetter, H. Kaberi, A. P. Karageorgis, E. Kastanidi, N. Katsiaras, A. Pavlidou, et al. 2022. Assessing pressure drivers on the benthic ecosystem in the coastal zone of Western Messinia, Greece. *Estuarine, Coastal and Shelf Science*. Elsevier Ltd: 138954.

Cabana, D., Sigala, K., Nicolaidou, A., Reizopoulou, S., 2013. Towards the implementation of the Water Framework Directive in Mediterranean transitional waters: the use of macroinvertebrates as biological quality elements. Adv Oceanogr Limnol 4, 212–240. https://doi.org/10.1080/19475721.2013.846279

Canu, D. M., P. Campostrini, S. Dalla Riva, R. Pastres, L. Pizzo, L. Rossetto, and C. Solidoro. 2011. Addressing Sustainability of Clam Farming in the Venice Lagoon. *Ecology and Society* 16.

Carafa, R., J. Wollgast, E. Canuti, J. Ligthart, S. Dueri, G. Hanke, S. J. Eisenreich, P. Viaroli, and J. M. Zaldívar. 2007. Seasonal variations of selected herbicides and related metabolites in water, sediment, seaweed and clams in the Sacca di Goro coastal lagoon (Northern Adriatic). *Chemosphere* 69: 1625–1637.

Cardoso, A. C., and G. Free. 2008. Incorporating invasive alien species into ecological assessment in the context of the water framework directive. *Aquatic Invasions* 3: 361–366.

Carlier, A., Riera, P., Amouroux, J.-M., Bodiou, J.-Y., Desmalades, M., & Grémare, A. (2008). Food web structure of two Mediterranean lagoons under varying degree of eutrophication. *Journal of Sea Research*, *60*(4), 264–275. https://doi.org/10.1016/j.seares.2008.10.006

Carlier, A., P. Riera, J. M. Amouroux, J. Y. Bodiou, M. Desmalades, and A. Gremare. 2009. Spatial heterogeneity in the food web of a heavily modified Mediterranean coastal lagoon: stable isotope evidence. *Aquatic Biology* 5: 167–179.

Carrier-Belleau, C., L. Pascal, C. Nozais, and P. Archambault. 2021. Tipping points and multiple drivers in changing aquatic ecosystems: A review of experimental studies. *Limnology and Oceanography* 9999: 1–19.

Carrozzo, L., L. Potenza, P. Carlino, M. L. Costantini, L. Rossi, and G. Mancinelli. 2014. Seasonal abundance and trophic position of the Atlantic blue crab Callinectes sapidus Rathbun 1896 in a Mediterranean coastal habitat. *Rendiconti Lincei* 25: 201–208.

Carvalho, L., E. B. Mackay, A. C. Cardoso, A. Baattrup-Pedersen, S. Birk, K. L. Blackstock, G. Borics, et al. 2019. Protecting and restoring Europe's waters: An analysis of the future development needs of the Water Framework Directive. *Science of the Total Environment* 658. Elsevier B.V.: 1228–1238.

Castaldelli, G., S. Mantovani, D. T. Welsh, R. Rossi, M. Mistri, and E. A. Fano. 2003. Impact of commercial clam harvesting on water column and sediment physicochemical characteristics and macrobenthic community structure in a lagoon (Sacca di Goro) of the Po river Delta. *Chemistry and Ecology* 19: 161–171.

Castel, J., Caumette, P., Herbert, R., 1996. Eutrophication gradients in coastal lagoons as exemplified by the Bassin d'Arcachon and the Étang du Prévost. Hydrobiologia 329. https://doi.org/10.1007/BF00034542

Cataudella, S., D. Crosetti, and F. Massa. 2015. Mediterranean coastal lagoons: sustainable management and interactions among aquaculture, capture fisheries and the environment. General Fisheries Commission for the Mediterranean. Studies and Reviews, (95), I.

Caumette, P., Baleux, B., 1980. Etude des eaux rouges dues à la prolifération des bactéries photosynthétiques sulfo-oxydantes dans l'étang du Prévost, lagune saumâtre méditerranéenne. Mar Biol 56, 183–194.

Caumette, P., J. Castel, and R. Herbert. 1996. Coastal lagoon eutrophication and anaerobic processes (C.L.E.A.N.): Nitrogen and sulfur cycles and population dynamics in coastal lagoons. A research programme of the environment programme of the E.C. (DG XII). Springer Science & Business Media.

Cernansky, R. 2017. The biodiversity revolution. *Nature* 546: 22–24.

Cibic, T., A. Franzo, M. Celussi, C. Fabbro, and P. Del Negro. 2012. Benthic ecosystem functioning in hydrocarbon and heavy-metal contaminated sediments of an Adriatic lagoon. *Marine Ecology Progress Series* 458: 69–87.

Cloern, J.E., 2001. Our evolving conceptual model of the coastal eutrophication problem. Marine Ecology Progress Series 210, 223–253.

Coccioni, R., F. Frontalini, A. Marsili, and D. Mana. 2009. Benthic foraminifera and trace element distribution: A case-study from the heavily polluted lagoon of Venice (Italy). *Marine Pollution Bulletin* 59. Elsevier Ltd: 257–267.

Coll, M., C. Piroddi, J. Steenbeek, K. Kaschner, F. Ben Rais Lasram, J. Aguzzi, E. Ballesteros, et al. 2010. The Biodiversity of the Mediterranean Sea: Estimates, Patterns, and Threats. Edited by Steven J. Bograd. *PLoS ONE* 5: e11842.

Como, S., P. Magni, D. Casu, A. Floris, G. Giordani, S. Natale, G. A. Fenzi, G. Signa, and G. De Falco. 2007. Sediment characteristics and macrofauna distribution along a human-modified inlet in the Gulf of Oristano (Sardinia, Italy). *Marine Pollution Bulletin* 54: 733–744.

Como, S, A. Floris, A. Pais, P. Rumolo, S. Saba, M. Sprovieri, and P. Magni. 2018. Assessing the impact of the Asian mussel *Arcuatula senhousia* in the recently invaded Oristano Lagoon-Gulf system (W Sardinia, Italy). *Estuarine, Coastal and Shelf Science* 201. Vectors of Change in the Marine Environment: 123–131.

Como, Serena, and P. Magni. 2009. Temporal changes of a macrobenthic assemblage in harsh lagoon sediments. *Estuarine, Coastal and Shelf Science* 83. Academic Press: 638–646.

Côté, I. M., E. S. Darling, and C. J. Brown. 2016. Interactions among ecosystem stressors and their importance in conservation. *Proceedings of the Royal Society B: Biological Sciences* 283.

Cramer, W., J. Guiot, M. Fader, J. Garrabou, J.-P. Gattuso, A. Iglesias, M. A. A. Lange, et al. 2018. Climate change and interconnected risks to sustainable development in the Mediterranean. *Nature Climate Change* 8.

Dedieu, K., C. Rabouille, G. Thouzeau, F. Jean, L. Chauvaud, J. Clavier, V. Mesnage, and S. Ogier. 2007a. Benthic O2 distribution and dynamics in a Mediterranean lagoon (Thau, France): An *in situ* microelectrode study. *Estuarine, Coastal and Shelf Science* 72: 393–405.

Dedieu, K, Rabouille, C., Gilbert, F., Soetaert, K., Metzger, E., Simonucci, C., Jezequel, D., Prevot, F., Anschutz, P., Hulth, S., Ogier, S., Mesnage, V., 2007b. Coupling of carbon, nitrogen and oxygen cycles in sediments from a Mediterranean lagoon: a seasonal perspective. Mar Ecol Prog Ser 346, 45–59. https://doi.org/10.3354/meps07031

Derolez, V., A. Fiandrino, D. Munaron, and M. Cadoret. 2014. Bilan sur les principales pressions pesant sur les lagunes méditerranéennes et leurs liens avec l'état DCE. Rapport IFREMER.

Derolez, V., N. Malet, A. Fiandrino, F. Lagarde, M. Richard, V. Ouisse, B. Bec, and C. Aliaume. 2020. Fifty years of ecological changes: Regime shifts and drivers in a coastal Mediterranean lagoon during oligotrophication. *Science of the Total Environment* 732. Elsevier B.V: 183135.

Dethier, M. N., and S. D. Hacker. 2004. Improving management practices for invasive cordgrass in the Pacific Northwest: A case study of *Spartina anglica*. *Washington Sea Grant Publication*.

de Wit, R., Stal, L.J., Lomstein, B.A., Herbert, R.A., van Gemerden, H., Viaroli, P., Cecherelli, V.U., Rodríguez-Valera, F., Bartoli, M., Giordani, G., Azzoni, R., Schaub, B., Welsh, D.T., Donnelly, A., Cifuentes, A., Antón, J., Finster, K., Nielsen, L.B., Pedersen, A.G.U., Neubauer, A.T., Colangelo, M.A., Heijs, S.K., 2001. ROBUST: The ROle of BUffering capacities in STabilising coastal lagoon ecosystems. Cont Shelf Res 21, 2021–2041. https://doi.org/10.1016/S0278-4343(01)00040-1

De Wit, R., A. Leruste, I. Le Fur, M. M. Sy, B. Bec, V. Ouisse, V. Derolez, and H. Rey-Valette. 2020. A Multidisciplinary Approach for Restoration Ecology of Shallow Coastal Lagoons, a Case Study in South France. *Frontiers in Ecology and Evolution* 8.

Dolbeth, M., Pardal, M.A., Lillebø, A.I., Azeiteiro, U., Marques, J.C., 2003. Short- and long-term effects of eutrophication on the secondary production of an intertidal macrobenthic community. Mar Biol 143, 1229–1238. https://doi.org/10.1007/S00227-003-1133-5/TABLES/3

Duport, E., F. Gilbert, J. C. Poggiale, K. Dedieu, C. Rabouille, and G. Stora. 2007. Benthic macrofauna and sediment reworking quantification in contrasted environments in the Thau Lagoon. *Estuarine, Coastal and Shelf Science* 72: 522–533.

Durreau, A., L. Soissons, and V. Ouisse. 2021. Effet des épisodes extrêmes en milieu méditerranéen stressé. Phase 1: étude bibliographique et mise en place d'outils test *in situ*. 65p + Annexes. doi: 10.13155/80623

el Mahrad, B., Abalansa, S., Newton, A., Icely, J.D., Snoussi, M., Kacimi, I., 2020. Social-Environmental Analysis for the Management of Coastal Lagoons in North Africa. Front Environ Sci 8, 37. https://doi.org/10.3389/FENVS.2020.00037/BIBTEX

Espel, D., N. J. Diepens, O. Boutron, E. Buffan-Dubau, Y. Chérain, E. Coulet, P. Grillas, A. Probst, J. Silvestre, and A. Elger. 2019. Dynamics of the seagrass *Zostera noltei* in a shallow Mediterranean lagoon exposed to chemical contamination and other stressors. *Estuarine, Coastal and Shelf Science* 222: 1–12.

European Union, 2018. Commission Decision of February 12th 2018, in the Official Journal of the European Union https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018D0229&from=HU

Fastelli, P., and M. Renzi. 2019. Exposure of key marine species to sunscreens: Changing ecotoxicity as a possible indirect effect of global warming. *Marine Pollution Bulletin* 149. Pergamon: 110517.

Ferreira, J.G., Vale, C., Soares, C.V., Salas, F., Stacey, P.E., Bricker, S.B., Silva, M.C., Marques, J.C., 2007. Monitoring of coastal and transitional waters under the E.U. Water Framework Directive. Environ Monit Assess 135, 195–216. https://doi.org/10.1007/s10661-007-9643-0

Foster, W. J., E. Armynot du Châtelet, and M. Rogerson. 2012. Testing benthic foraminiferal distributions as a contemporary quantitative approach to biomonitoring estuarine heavy metal pollution. *Marine Pollution Bulletin* 64: 1039–1048.

Franzo, A., R. Auriemma, F. Nasi, J. Vojvoda, A. Pallavicini, T. Cibic, and P. Del Negro. 2016. Benthic ecosystem functioning in the severely contaminated Mar Piccolo of Taranto (Ionian Sea, Italy): focus on heterotrophic pathways. *Environmental Science and Pollution Research* 23. Springer Verlag: 12645–12661.

Le Fur, I. 2018. Rôle des macrophytes dans la restauration des milieux lagunaires : successions écologiques. Thèse de doctorat. Université de Montpellier.

Le Fur, I., de Wit, R., Plus, M., Oheix, J., Simier, M., Ouisse, V., 2018. Submerged benthic macrophytes in Mediterranean lagoons: distribution patterns in relation to water chemistry and depth. Hydrobiologia 808, 175–200. https://doi.org/10.1007/S10750-017-3421-Y/FIGURES/7

Le Fur, I., R. de Wit, M. Plus, J. Oheix, V. Derolez, M. Simier, N. Malet, and V. Ouisse. 2019. Re-oligotrophication trajectories of macrophyte assemblages in Mediterranean coastal lagoons studied from 17-years' time-series. *Marine Ecology Progress Series* 608: 13–32.

Gagic, V., I. Bartomeus, T. Jonsson, A. Taylor, C. Winqvist, C. Fischer, E. M. Slade, et al. 2015. Functional identity and diversity of animals predict ecosystem functioning better than species-based indices. *Proceedings of the Royal Society B: Biological Sciences* 282: 20142620.

Galgani, F., J. Senia, J. L. Guillou, T. Laugier, D. Munaron, B. Andral, B. Guillaume, et al. 2009. Assessment of the environmental quality of french continental mediterranean lagoons with oyster embryo bioassay. *Archives of Environmental Contamination and Toxicology* 57: 540–551.

Gallardi, D. 2014. Effects of Bivalve Aquaculture on the Environment and Their Possible Mitigation : A Review. *Fisheries and Aquaculture Journal* 5: 8.

García-Sánchez, M., I. M. Pérez-Ruzafa, C. Marcos, and A. Pérez-Ruzafa. 2012. Suitability of benthic macrophyte indices (EEI, E-MaQI and BENTHOS) for detecting anthropogenic pressures in a Mediterranean coastal lagoon (Mar Menor, Spain). *Ecological Indicators* 19: 48–60.

Ghezzo, M., M. Pellizzato, F. De Pascalis, S. Silvestri, and G. Umgiesser. 2018. Natural resources and climate change: A study of the potential impact on Manila clam in the Venice lagoon. *Science of the Total Environment* 645. Elsevier B.V.: 419–430.

Gissi, E., E. Manea, A. D. Mazaris, S. Fraschetti, V. Almpanidou, S. Bevilacqua, M. Coll, et al. 2021. A review of the combined effects of climate change and other local human stressors on the marine environment. *Science of the Total Environment*. Elsevier.

Green, D. S., B. Boots, J. Sigwart, S. Jiang, and C. Rocha. 2016. Effects of conventional and biodegradable microplastics on a marine ecosystem engineer (*Arenicola marina*) and sediment nutrient cycling. *Environmental Pollution* 208. Elsevier: 426–434.

Halpern, B. S., Frazier, M., Potapenko, J., Casey, K. S., Koenig, K., Longo, C., ... & Walbridge, S. 2015. Spatial and temporal changes in cumulative human impacts on the world's ocean. *Nature communications*, *6*(1), 1-7.

Harzallah, A., and A. Chapelle. 2002. Contribution of climate variability to occurrences of anoxic crises "malaïgues" in the Thau lagoon (southern France). *Oceanologica Acta* 25: 79–86.

Ieno, E. N., Solan, M., Batty, P., & Pierce, G. J. 2006. How biodiversity affects ecosystem functioning: roles of infaunal species richness, identity and density in the marine benthos. *Marine Ecology Progress Series*, *311*, 263-271

IPBES (2019): Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. E. S. Brondizio, J. Settele, S. Díaz, and H. T. Ngo (editors). IPBES secretariat, Bonn, Germany. 1148 pages. https://doi.org/10.5281/zenodo.3831673

Isbell, F., A. Gonzalez, M. Loreau, J. Cowles, S. Díaz, A. Hector, G. M. MacE, et al. 2017. Linking the influence and dependence of people on biodiversity across scales. *Nature* 546: 65–72.

de Jonge, V. N., and M. Elliott. 2001. Eutrophication. *Encyclopedia of Ocean Sciences* 2: 852–870.

Jones, A., Schaal, G., Boyé, A., Creemers, M., Derolez, V., Desroy, N., Fiandrino, A., Mouton, T.L., Simier, M., Smith, N., Ouisse, V., 2022. PREPRINT. Disentangling the effects of eutrophication and natural variability on macrobenthic communities across French coastal lagoons. https://doi.org/10.1101/2022.08.18.504439

El Kateb, A., C. Stalder, C. Neururer, R. Fentimen, J. E. Spangenberg, and S. Spezzaferri. 2018. Distribution of benthic foraminiferal assemblages in the transitional environment of the Djerba lagoon (Tunisia). *Swiss Journal of Geosciences* 111. Birkhauser Verlag AG: 561–578.

Khedhri, I., A. Afli, and L. Aleya. 2017. Structuring factors of the spatio-temporal variability of macrozoobenthos assemblages in a southern Mediterranean lagoon: How useful for bioindication is a multi-biotic indices approach? *Marine Pollution Bulletin* 114: 515–527.

Khedhri, I., H. Djabou, and A. Afli. 2015. Trophic and functional organization of the benthic macrofauna in the lagoon of Boughrara - Tunisia (SW Mediterranean Sea). *Journal of the Marine Biological Association of the United Kingdom* 95: 647–659.

Khedhri, I., H. Djabou, and A. Afli. 2016. Does increased connectivity with the Mediterranean Sea improve the ecological status of the macroinvertebrates in the lagoon of Boughrara (SW Mediterranean)? *Community Ecology* 17: 156–166.

Korpinen, S., L. Laamanen, L. Bergström, M. Nurmi, J. H. Andersen, J. Haapaniemi, E. T. Harvey, et al. 2021. Combined effects of human pressures on Europe's marine ecosystems. *Ambio* 50: 1325–1336.

Kristensen, P., Whalley, C., Zal, F.N.N., Christiansen, T., 2018. European waters Assessment of status and pressures 2018. EEA Report No 7/2018

Kyselý, J., S. Beguería, R. Beranová, L. Gaál, and J. I. López-Moreno. 2012. Different patterns of climate change scenarios for short-term and multi-day precipitation extremes in the Mediterranean. *Global and Planetary Change* 98–99: 63–72.

Lacoste, É., B. Bec, P. Le Gall, F. Boufahja, P. Raimbault, G. Messiaen, V. Ouisse, et al. 2022. Benthic-pelagic coupling under juvenile oyster influence in a French Mediterranean coastal lagoon (Thau Lagoon). *Estuarine, Coastal and Shelf Science* 267.

Lacoste, É., F. Boufahja, C. Pelaprat, P. Le Gall, T. Berteaux, G. Messiaen, S. Mortreux, et al. 2020. First simultaneous assessment of macro- and meiobenthic community response to juvenile shellfish culture in a Mediterranean coastal lagoon (Thau, France). *Ecological Indicators* 115.

Lacoste, É., and N. Gaertner-Mazouni. 2015. Biofouling impact on production and ecosystem functioning: A review for bivalve aquaculture. *Reviews in Aquaculture* 7: 187–196.

Lacoste, É., C. W. McKindsey, P. Archambault. 2020. Biodiversity–Ecosystem Functioning (BEF) approach to further understanding aquaculture–environment interactions with application to bivalve culture and benthic ecosystems. *Reviews in Aquaculture* 12:4, 2027-2041. Doi: 10.1111/raq.12420

Lam-Gordillo, O., R. Baring, and S. Dittmann. 2020. Ecosystem functioning and functional approaches on marine macrobenthic fauna: A research synthesis towards a global consensus. *Ecological Indicators*. Elsevier.

Leenhardt, S., Mamy, L., Pesce, S., Sanchez, W., …, Tournebize, J., 2022. Impacts des produits phytopharmaceutiques sur la biodiversité et les services écosystémiques. Synthèse du rapport d'ESCo, INRAE - Ifremer (France).

León, V. M., R. Moreno-González, V. García, and J. A. Campillo. 2017. Impact of flash flood events on the distribution of organic pollutants in surface sediments from a Mediterranean coastal lagoon (Mar Menor, SE Spain). *Environmental Science and Pollution Research* 24. Springer Verlag: 4284–4300.

Lloret, J., A. Marín, and L. Marín-Guirao. 2008. Is coastal lagoon eutrophication likely to be aggravated by global climate change? *Estuarine, Coastal and Shelf Science* 78: 403–412.

Magri, M., Benelli, S., Bonaglia, S., Zilius, M., Castaldelli, G., Bartoli, M., 2020. The effects of hydrological extremes on denitrification, dissimilatory nitrate reduction to ammonium (DNRA) and mineralization in a coastal lagoon. Science of The Total Environment 740, 140169. https://doi.org/10.1016/j.scitotenv.2020.140169

Mahé, M., D. Delanghe, R. Grisel, J. Poggiale, M. 2021. Distribution of Manila clam, *Ruditapes philippinarum*, into Berre Lagoon according to the environmental condition. *Vie et milieu*.

Mahmoudi, E., A. Hedfi, N. Essid, H. Beyrem, P. Aïssa, F. Boufahja, and P. Vitiello. 2008. Mussel-farming effects on Mediterranean benthic nematode communities. *Nematology* 10: 323–333

Mancinelli, G., L. Carrozzo, M. L. Costantini, L. Rossi, G. Marini, and M. Pinna. 2013. Occurrence of the Atlantic blue crab *Callinectes sapidus* Rathbun, 1896 in two Mediterranean coastal habitats: Temporary visitor or permanent resident? *Estuarine Coastal and Shelf Science* 135: 46–56.

Mancinelli, G., P. Chainho, L. Cilenti, S. Falco, K. Kapiris, G. Katselis, and F. Ribeiro. 2017. The Atlantic blue crab *Callinectes sapidus* in southern European coastal waters: Distribution, impact and prospective invasion management strategies. *Marine Pollution Bulletin* 119: 5–11.

Maneas, G., E. Makopoulou, D. Bousbouras, H. Berg, and S. Manzoni. 2019. Anthropogenic changes in a Mediterranean Coastal Wetland during the last century—The case of Gialova Lagoon, Messinia, Greece. *Waters* 11: 350.

Mantovani, S., G. Castaldelli, R. Rossi, and E. A. Fano. 2006. The infaunal community in experimentally seeded low and high density Manila clam (*Tapes philippinarum*) beds in a Po River Delta lagoon (Italy). *Ices Journal of Marine Science* 63: 860–866.

Marchessaux, G., B. Belloni, J. Gadreaud, and D. Thibault. 2021a. Predation assessment of the invasive ctenophore *Mnemiopsis leidyi* in a French Mediterranean lagoon. *Journal of Plankton Research* 43: 161–179.

Marchessaux, G., M. Harmelin-Vivien, M. Ourgaud, D. Bănaru, L. Guilloux, B. Belloni, B. Lebreton, G. Guillou, and D. Thibault. 2021b. First overview on trophic relationships of the invasive ctenophore *Mnemiopsis leidyi* in a Mediterranean coastal lagoon (Berre Lagoon, France): benthic–pelagic coupling evidenced by carbon and nitrogen stable isotope composition. *Regional Studies in Marine Science* 41: 101570.

De Marchi, L., L. R. Vieira, L. Intorre, V. Meucci, F. Battaglia, C. Pretti, A. M. V. M. Soares, and R. Freitas. 2022. Will extreme weather events influence the toxic impacts of caffeine in coastal systems? Comparison between two widely used bioindicator species. *Chemosphere* 297. Pergamon: 134069.

Marchini, A., J. Ferrario, A. Sfriso, and A. Occhipinti-Ambrogi. 2015. Current status and trends of biological invasions in the Lagoon of Venice, a hotspot of marine NIS introductions in the Mediterranean Sea. *Biological Invasions* 17: 2943–2962.

Marín-Guirao, L., A. Cesar, A. Marín, and R. Vita. 2005. Assessment of sediment metal contamination in the Mar Menor coastal lagoon (SE Spain): Metal distribution, toxicity, bioaccumulation and benthic community structure. *Ciencias Marinas* 31: 413–428.

Martin, S., G. Thouzeau, M. Richard, L. Chauvaud, F. Jean, and J. Clavier. 2007. Benthic community respiration in areas impacted by the invasive mollusk *Crepidula fornicata*. *Marine Ecology Progress Series* 347: 51–60.

Martins, M. V. A., Helali, M.A., Zaaboub, N., I. Boukef-BenOmrane, F. Frontalini, D. Reis, H. Portela, et al. 2016. Organic matter quantity and quality, metals availability and foraminiferal assemblages as environmental proxy applied to the Bizerte Lagoon (Tunisia). *Marine Pollution Bulletin* 105: 161–179.

Mason, N. W. H., D. Mouillot, W. G. Lee, and J. B. Wilson. 2005. Functional richness, functional evenness and functional divergence: The primary components of functional diversity. *Oikos* 111: 112–118.

Mazor, T., C. Doropoulos, F. Schwarzmueller, D. W. Gladish, N. Kumaran, K. Merkel, M. Di Marco, and V. Gagic. 2018. Global mismatch of policy and research on drivers of biodiversity loss. *Nature Ecology and Evolution* 2. Springer US: 1071–1074.

Millenium Ecosystem Assessement, 2005. Ecosystems and human well-being: synthesis. Island Press, Washington, DC.

Mercurio, M., C. Pierri, F. Cardone, and G. Corriero. 2021. Temporal and spatial variations of G*eodia cydonium* (Jameson) (porifera, demospongiae) in the mediterranean confined environments. *Diversity* 13.

Metzger, E., C. Simonucci, E. Viollier, G. Sarazin, F. Prevot, and D. Jezequel. 2007. Benthic response to shellfish farming in Thau lagoon: Pore water signature. *Estuarine Coastal and Shelf Science* 72: 406–419.

Meyer, S. T., C. Koch, and W. W. Weisser. 2015. Towards a standardized Rapid Ecosystem Function Assessment (REFA). *Trends in Ecology and Evolution* 30. Elsevier Ltd: 390–397.

Micheli, F., B. S. Halpern, S. Walbridge, S. Ciriaco, F. Ferretti, S. Fraschetti, R. Lewison, L. Nykjaer, and A. A. Rosenberg. 2013. Cumulative human impacts on Mediterranean and Black Sea marine ecosystems: Assessing current pressures and opportunities. *PLoS ONE* 8.

Miller, D. C., C. L. Muir, and O. A. Hauser. 2002. Detrimental effects of sedimentation on marine benthos: What can be learned from natural processes and rates? *Ecological Engineering* 19: 211–232.

Mistri, M. 2003. The non-indigenous mussel *Musculista senhousia* in an Adriatic lagoon: effects on benthic community over a ten year period. *Journal of the Marine Biological Association of the United Kingdom* 83: 1277–1278.

Mistri, M., and C. Munari. 2012. Clam farming generates CO2: A study case in the Marinetta lagoon (Italy). *Marine Pollution Bulletin* 64: 2261–2264.

Morant, D., Perennou, C., Camacho, A., 2021. Assessment of the Pressure Level over Lentic Waterbodies through the Estimation of Land Uses in the Catchment and Hydro-Morphological Alterations: The LUPLES Method. Applied Sciences 11, 1633. https://doi.org/10.3390/app11041633

Moreno-González, R., and V. M. León. 2017. Presence and distribution of current-use pesticides in surface marine sediments from a Mediterranean coastal lagoon (SE Spain). *Environmental Science and Pollution Research* 24. Springer Verlag: 8033–8048.

Moreno, M., F. Semprucci, L. Vezzulli, M. Balsamo, M. Fabiano, and G. Albertelli. 2011. The use of nematodes in assessing ecological quality status in the Mediterranean coastal ecosystems. *Ecological Indicators* 11. Elsevier: 328–336.

Moschino, V., L. Chicharo, and M. G. Marin. 2011. Long-term effects of fishing on physiological performance of the Manila clam (*Ruditapes philippinarum*) in the Lagoon of Venice. *Scientia Marina* 75: 103–110..

Munari, C., and M. Mistri. 2008. The performance of benthic indicators of ecological change in Adriatic coastal lagoons: Throwing the baby with the water? *Marine Pollution Bulletin* 56. Pergamon: 95–105.

Munari, C, and M. Mistri. 2014. Spatio-temporal pattern of community development in dredged material used for habitat enhancement: A study case in a brackish lagoon. *Marine pollution bulletin* 89. Elsevier Ltd: 340–7.

Munari, Cristina. 2008. Effects of the exotic invader *Musculista senhousia* on benthic communities of two Mediterranean lagoons. *Hydrobiologia* 611: 29–43.

Munari, Cristina. 2011. Effects of the 2003 European heatwave on the benthic community of a severe transitional ecosystem (Comacchio Saltworks, Italy). *Marine Pollution Bulletin* 62. Pergamon: 2761–2770.

Murphy, A.E., Nizzoli, D., Bartoli, M., Smyth, A.R., Castaldelli, G., Anderson, I.C., 2018. Variation in benthic metabolism and nitrogen cycling across clam aquaculture sites. Mar Pollut Bull 127, 524–535. https://doi.org/10.1016/j.marpolbul.2017.12.003

Nasi, F., M. C. Nordström, E. Bonsdorff, R. Auriemma, T. Cibic, and P. Del Negro. 2018. Functional biodiversity of marine soft-sediment polychaetes from two Mediterranean coastal areas in relation to environmental stress. *Marine Environmental Research* 137: 121–132.

Nebot-Colomer, E., Álvarez, E., Belando, M.D., Deudero, S., Catanese, G., Bernardeau-Esteller, J., García-Muñoz, R., Ramos-Segura, A., Ruiz, J.M., Vázquez-Luis, M., 2022. Living under threat: Will one of the last *Pinna nobili*s populations be able to survive? Aquat Conserv 32, 1–13. https://doi.org/10.1002/aqc.3738

Newton, A., A. C. Brito, J. D. Icely, V. Derolez, I. Clara, S. Angus, G. Schernewski, et al. 2018. Assessing, quantifying and valuing the ecosystem services of coastal lagoons. *Journal for Nature Conservation* 44. Elsevier GmbH.: 50–65.

Newton, A., J. Icely, S. Cristina, A. Brito, A. C. Cardoso, F. Colijn, S. D. Riva, et al. 2014. An overview of ecological status, vulnerability and future perspectives of European large shallow, semi-enclosed coastal systems, lagoons and transitional waters. *Estuarine, Coastal and Shelf Science* 140. Academic Press: 95–122.

Nizzoli, D, M. Bartoli, and P. Viaroli. 2006a. Nitrogen and phosphorus budgets during a farming cycle of the Manila clam *Ruditapes philippinaru*m: An in situ experiment. *Aquaculture* 261: 98–108.

Nizzoli, D, M. Bartoli, and P. Viaroli. 2007. Oxygen and ammonium dynamics during a farming cycle of the bivalve *Tapes philippinarum*. *Hydrobiologia* 587: 25–36.

Nizzoli, Daniele, D. T. Welsh, M. Bartoli, and P. Viaroli. 2005. Impacts of mussel (*Mytilus galloprovincialis*) farming on oxygen consumption and nutrient recycling in a eutrophic coastal lagoon. In *Hydrobiologia*, 550:183–198.

Nizzoli, Daniele, D. T. Welsh, E. A. Fano, and P. Viaroli. 2006b. Impact of clam and mussel farming on benthic metabolism and nitrogen cycling, with emphasis on nitrate reduction pathways. *Marine Ecology Progress Series* 315: 151–165.

Nizzoli, Daniele, D. Welsh, and P. Viaroli. 2011. Seasonal nitrogen and phosphorus dynamics during benthic clam and suspended mussel cultivation. *Marine pollution bulletin* 62. Elsevier Ltd: 1276–87.

Nonnis Marzano, C., L. Scalera Liaci, A. Fianchini, F. Gravina, M. Mercurio, and G. Corriero. 2003. Distribution, persistence and change in the macrobenthos of the lagoon of Lesina (Apulia, southern Adriatic Sea). *Oceanologica Acta* 26: 57–66.

von der Ohe, P. C., V. Dulio, J. Slobodnik, E. De Deckere, R. Kühne, R. U. Ebert, A. Ginebreda, W. De Cooman, G. Schüürmann, and W. Brack. 2011. A new risk assessment approach for the prioritization of 500 classical and emerging organic microcontaminants as potential river basin specific pollutants under the European Water Framework Directive. *Science of the Total Environment* 409. Elsevier: 2064–2077.

Orabi, O. H., A. A. El-Badry, and A. M. Badr-ElDin. 2017. Benthic foraminifera for heavy metal pollution monitoring: A case study from Burullus Lagoon of Egypt. *Marine Pollution Bulletin* 121: 411–417.

Orfanidis, S., Dencheva, K., Nakou, K., Tsioli, S., Papathanasiou, V., Rosati, I., 2014. Benthic macrophyte metrics as bioindicators of water quality: towards overcoming typological boundaries and methodological tradition in Mediterranean and Black Seas. Hydrobiologia. https://doi.org/10.1007/s10750-014-1938-x

Ouisse, V., A. Fiandrino, R. De Wit, and A. Giraud. 2014. *DEvenir du Phosphore et de l ' Azote dans un contexte de ResTauration des milieux lagunaires méditerranéens - DEPART –*. Vol. 3211998.

Ouisse, V., A. Fiandrino, R. de Wit, and N. Malet. 2013. *Restauration des écosystèmes lagunaires : évaluation du rôle du sédiment et des herbiers à phanérogames Rapport final du Contrat n° 2012 1835*.

Pasqualini, V., V. Derolez, M. Garrido, V. Orsoni, Y. Baldi, S. Etourneau, V. Leoni, et al. 2017. Spatiotemporal dynamics of submerged macrophyte status and watershed exploitation in a Mediterranean coastal lagoon: Understanding critical factors in ecosystem degradation and restoration. *Ecological Engineering* 102. Elsevier B.V.: 1–14.

Pearson, T.H., Rosenberg, R., 1978. Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. Oceanography and marine biology annual review 16, 229–311. https://doi.org/10.1111/j.1540-5834.2012.00707.x

Pérez-Ruzafa, Angel, I. M. Pérez-Ruzafa, A. Newton, and C. Marcos. 2019. Coastal Lagoons: Environmental Variability, Ecosystem Complexity, and Goods and Services Uniformity. In *Coasts and Estuaries*, ed. E. Wolanski, J. W. Day, M. Elliott, and R. Ramachandran, 253–276. Elsevier.

Pitacco, V., M. Mistri, C. R. Ferrari, A. Sfriso, A. A. Sfriso, and C. Munari. 2020. Multiannual trend of micro-pollutants in sediments and benthic community response in a mediterranean lagoon (Sacca di Goro, Italy). *Water (Switzerland)* 12.

Pitacco, V., M. Mistri, and C. Munari. 2018. Long-term variability of macrobenthic community in a shallow coastal lagoon (Valli di Comacchio, northern Adriatic): Is community resistant to climate changes? *Marine Environmental Research* 137. Elsevier: 73–87.

Poikane, S., F. Salas Herrero, M. G. Kelly, A. Borja, S. Birk, and W. van de Bund. 2020. European aquatic ecological assessment methods: A critical review of their sensitivity to key pressures. *Science of the Total Environment* 740. The Authors: 140075.

Ponti, M., A. Pasteris, R. Guerra, and M. Abbiati. 2009. Impacts of maintenance channel dredging in a northern Adriatic coastal lagoon. II: Effects on macrobenthic assemblages in channels and ponds. *Estuarine, Coastal and Shelf Science* 85: 143–150.

Pranovi, F., Giovanardi, O., & Franceschini, G. 1998. Recolonization dynamics in areas disturbed by bottom fishing gears. *Hydrobiologia*, *375–76*, 125–135. https://doi.org/10.1023/a:1017056905625

Pranovi, F., da Ponte, F., Raicevich, S., Giovanardi, O. 2004. A multidisciplinary study of the immediate effects of mechanical clam harvesting in the Venice Lagoon. ICES Journal of Marine Science, 61(1), 43–52. https://doi.org/10.1016/j.icesjms.2003.10.003

Pranovi, F., G. Franceschini, M. Casale, M. Zucchetta, P. Torricelli, and O. Giovanardi. 2006. An Ecological Imbalance Induced by a Non-Native Species: The Manila Clam in the Venice Lagoon. *Biological Invasions* 8: 595–609.

Quevauviller, P. 2011. Adapting to climate change: Reducing water-related risks in Europe - EU policy and research considerations. *Environmental Science and Policy* 14. Elsevier: 722–729.

Quigley, M. P., and J. A. Hall. 1999. Recovery of macrobenthic communities after maintenance dredging in the Blyth estuary, north-east England. *Aquatic Conservation: Marine and Freshwater Ecosystems* 9: 63–73.

Ragueneau, O., L. Chauvaud, B. Moriceau, A. Leynaert, G. Thouzeau, A. Donval, F. Le Loc'h, and F. Jean. 2005. Biodeposition by an invasive suspension feeder impacts the biogeochemical cycle of Si in a coastal ecosystem (Bay of Brest, France). *Biogeochemistry* 75. Springer: 19–41.

Renzi, M., V. H. Pauna, F. Provenza, C. Munari, and M. Mistri. 2020. Marine litter in transitional water ecosystems: State of the art review based on a bibliometric analysis. *Water (Switzerland)* 12.

Reyjol, Y., C. Argillier, W. Bonne, A. Borja, A. D. Buijse, A. C. Cardoso, M. Daufresne, et al. 2014. Assessing the ecological status in the context of the European Water Framework Directive: Where do we go now? *Science of the Total Environment* 497–498. Elsevier B.V.: 332–344.

Rigaud, S., J. M. Garnier, X. Moreau, L. De Jong-Moreau, N. Mayot, P. Chaurand, and O. Radakovitch. 2019. How to assess trace elements bioavailability for benthic organisms in lowly to moderately contaminated coastal sediments? *Marine Pollution Bulletin* 140: 86–100.

Rigaud, S., Deflandre, B., Grenz, C., Cesbron, F., Pozzato, L., Voltz, B., Grémare, A., Romero-Ramirez, A., Mirleau, P., Meulé, S., Faure, V., Mayot, N., Michotey, V., Bonin, P., Pascal, L., Cordier, M.-A., Lamarque, B., Tenório, M., Radakovitch, O., 2021. Benthic oxygen dynamics and implication for the maintenance of chronic hypoxia and ecosystem degradation in the Berre lagoon (France). Estuar Coast Shelf Sci 258, 107437. https://doi.org/10.1016/j.ecss.2021.107437

Rigaud, S., Giorgio, C. di, Radakovitch, O., Garnier, J.M., Méo, M. de, 2012. Genotoxicity of sediment extracts of the Berre lagoon (France). Chemosphere 88, 937–944. https://doi.org/10.1016/j.chemosphere.2012.03.023

Rhoads, D., McCall, P., Yingst, J., 1978. Disturbance and Production on the Estuarine Seafloor: Dredge-spoil disposal in estuaries such as Long Island Sound can be managed in ways that enhance. Am Sci 66, 577586.

Ruiz, F., M. L. González-Regalado, E. Galán, M. I. González, M. I. Prudencio, M. I. Dias, M. Abad, A. Toscano, J. Prenda, and E. X. M. García. 2012. Benthic foraminifera as bioindicators of anthropogenic impacts in two North African Lagoons: A comparison with ostracod assemblages. *Revista Mexicana de Ciencias Geologicas* 29: 527–533.

Rysgaard, S., Risgaard-Petersen, N., Sloth, N.P., 1996. Nitrification, denitrification, and nitrate ammonification in sediments of two coastal lagoons in Southern France. Hydrobiologia 329, 133–141. https://doi.org/10.1007/BF00034553

Said, O. Ben, M. Goñi-Urriza, M. El Bour, P. Aissa, and R. Duran. 2010. Bacterial community structure of sediments of the bizerte lagoon (Tunisia), a southern mediterranean coastal anthropized lagoon. *Microbial Ecology* 59: 445–456.

Saidi, I., O. Ben Said, J. Ben Abdelmalek, S. Jouili, L. Chicharo, and H. Beyrem. 2019. Impact of heavy metals of industrial plant wastewater on benthic communities of Bizerte Lagoon (Tunisia). *Chemistry and Ecology* 35: 746–774.

Ben Salem, F., O. Ben Said, C. Cravo-Laureau, E. Mahmoudi, N. Bru, M. Monperrus, and R. Duran. 2019. Bacterial community assemblages in sediments under high anthropogenic pressure at Ichkeul Lake/Bizerte Lagoon hydrological system, Tunisia. *Environmental Pollution* 252: 644–656.

Schmidt, S., J. L. Gonzalez, P. Lecroart, J. Tronczynski, I. Billy, and J. M. Jouanneau. 2007. Bioturbation at the water-sediment interface of the Thau Lagoon: impact of shellfish farming. *Aquatic Living Resources* 20: 163–169.

Schramm, W., 1999. Factors influencing seaweed responses to eutrophication : some results from EU-project EUMAC. J Appl Phycol 11, 69–78.

Semprucci, F., V. Losi, and M. Moreno. 2015. A review of Italian research on free-living marine nematodes and the future perspectives on their use as Ecological Indicators (EcoInds). *Mediterranean Marine Science*. Hellenic Centre for Marine Research.

Sfriso, A, F. Chiara, and M. Antonio. 2005. Sedimentation rates and erosion processes in the lagoon of Venice. *Environment International* 31. Lagoon of Venice: Loads, Distribution, and Effects of Nutrients and Pollutants: 983–992.

Sfriso, A, C. Facca, and P. Ghetti. 2003. Temporal and spatial changes of macroalgae and phytoplankton in a Mediterranean coastal area: the Venice lagoon as a case study. *Marine Environmental Research* 56: 617–636.

Sfriso, A., Facca, C., Ghetti, P.F., 2009. Validation of the Macrophyte Quality Index (MaQI) set up to assess the ecological status of Italian marine transitional environments. Hydrobiologia 617, 117–141. https://doi.org/10.1007/s10750-008-9540-8

Sfriso, A, M. A. Wolf, S. Maistro, K. Sciuto, and I. Moro. 2012. Spreading and autoecology of the invasive species *Gracilaria vermiculophylla* (Gracilariales, Rhodophyta) in the lagoons of the north-western Adriatic Sea (Mediterranean Sea, Italy). *Estuarine, Coastal and Shelf Science* 114. Research and Management for the Conservation of Coastal Lagoon Ecosystems: 192–198.

Sfriso, Adriano, A. Buosi, M. A. Wolf, and A. A. Sfriso. 2020. Invasion of alien macroalgae in the venice lagoon, a pest or a resource? *Aquatic Invasions* 15: 245–270.

Simboura, N., and S. Reizopoulou. 2008. An intercalibration of classification metrics of benthic macroinvertebrates in coastal and transitional ecosystems of the Eastern Mediterranean ecoregion (Greece). *Marine Pollution Bulletin* 56: 116–126.

Solan, M., Cardinale, B. J., Downing, A. L., Engelhardt, K. A., Ruesink, J. L., & Srivastava, D. S. 2004. Extinction and ecosystem function in the marine benthos. *Science*, *306*(5699), 1177-1180.

Souchu, P., Gasc, A., Collos, Y., Vaquer, A., Tournier, H., Bibent, B., Deslous-Paoli, J., 1998. Biogeochemical aspects of bottom anoxia in a Mediterranean lagoon (Thau, France). Mar Ecol Prog Ser 164, 135–146. https://doi.org/10.3354/meps164135

Stachowitsch, M. 1992. Benthic communities: Eutrophication's "memory mode". In Marine Coastal Eutrophication (Ed., Vollenwieder, R.A., Marchetti, R., Viviani, R.). Elsevier, Amsterdam, London, New York, Tokyo. pp. 1017-1028.

Streftaris, N., and A. Zenetos. 2006. Alien Marine Species in the Mediterranean - the 100 'Worst Invasives' and their Impact. *Mediterranean Marine Science* 7: 87–118.

Strong, J. A., E. Andonegi, K. C. K. Bizsel, R. Danovaro, M. Elliott, A. Franco, E. Garces, et al. 2015. Marine biodiversity and ecosystem function relationships: The potential for practical monitoring applications. *Estuarine, Coastal and Shelf Science* 161: 46–64.

Telahigue, K., I. Rabeh, L. Chouba, Z. Mdaini, M. El Cafsi, L. Mhadhbi, and T. Hajji. 2022. Assessment of the heavy metal levels and biomarker responses in the smooth scallop *Flexopecten glaber* from a heavily urbanized Mediterranean lagoon (Bizerte lagoon). *Environmental Monitoring and Assessment* 194. Springer Science and Business Media Deutschland GmbH.

Thouzeau, G., J. Grall, J. Clavier, L. Chauvaud, F. Jean, A. Leynaert, S. ni Longphuirt, E. Amice, and D. Amouroux. 2007. Spatial and temporal variability of benthic biogeochemical fluxes associated with macrophytic and macrofaunal distributions in the Thau lagoon (France). *Estuarine, Coastal and Shelf Science* 72: 432–446.

Troussellier, M., Deslous-Paoli, J.M., 2001. La lagune de Thau: un site atelier pour l'acquisition, l'intégration et la valorisation des connaissances. Oceanis 27, 257–289.

Tlig-Zouari, S., L. Rabaoui, A. Cosentino, I. Irathni, H. Ghrairi, and O. K. Ben Hassine. 2011. Macrofauna associated with an introduced oyster, Pinctada radiata: Spatial scale implications of community differences. *Journal of Sea Research* 65. Elsevier B.V.: 161–169.

Underwood, A. J. 1994. On beyond BACI: Sampling designs that might reliably detect environmental disturbances. *Ecological Applications* 4. John Wiley & Sons, Ltd: 3–15.

Viaroli, P, M. Bartoli, G. Giordani, R. Azzoni, and D. Nizzoli. 2003. Short term changes of benthic fluxes during clam harvesting in a coastal lagoon (Sacca di Goro, po river delta). *Chemistry and Ecology* 19: 189–206.

Viaroli, P, M. Bartoli, G. Giordani, and M. Naldi. 2008. Community shifts, alternative stable states, biogeochemical controls and feedbacks in eutrophic coastal lagoons : a brief overview. *Aquatic Conservation: MArine and Freshwater Ecosystems* 18: 105–117.

Vignes, F., E. Barbone, P. Breber, R. D'Adamo, R. Leonilde, N. Ungaro, S. Focardi, M. Renzi, and A. Basset. 2009. Spatial and temporal description of the dystrophic crisis in Lesina lagoon during summer 2008. *Transitional Waters Bulletin* 3: 47–62.

Zaaboub, N., M. V. A. Martins, A. Dhib, B. Béjaoui, F. Galgani, M. El Bour, and L. Aleya. 2015. Accumulation of trace metals in sediments in a Mediterranean Lagoon: Usefulness of metal sediment fractionation and elutriate toxicity assessment. *Environmental Pollution* 207: 226–237.

Zaldívar, J., A. C. Cardoso, P. Viaroli, R. De Wit, C. Ibañez, S. Reizopoulou, A. Razinkovas, A. Basset, M. Holmer, and N. Murray. 2008. Eutrophication in transitional waters : an overview. *Transitional Waters Monographs* 1: 1–78.

Zilius, M., G. Giordani, J. Petkuviene, I. Lubiene, T. Ruginis, and M. Bartoli. 2015. Phosphorus mobility under short-term anoxic conditions in two shallow eutrophic coastal systems (Curonian and Sacca di Goro lagoons). *Estuarine, Coastal and Shelf Science* 164. Academic Press: 134–146.

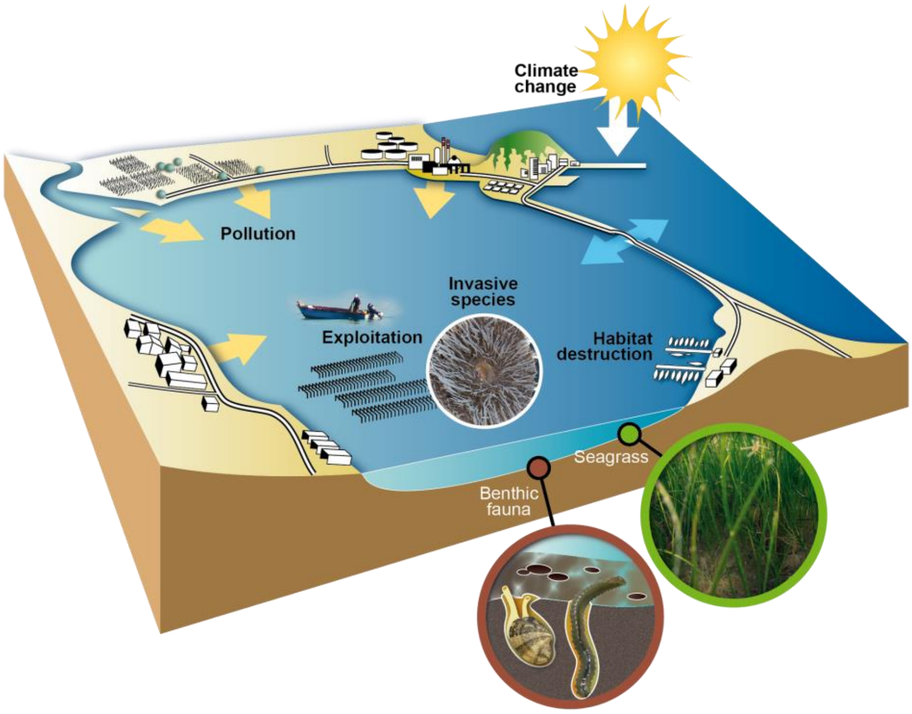

Figure 1. The five main anthropogenic pressures potentially impacting coastal lagoon soft-bottom benthic ecosystems

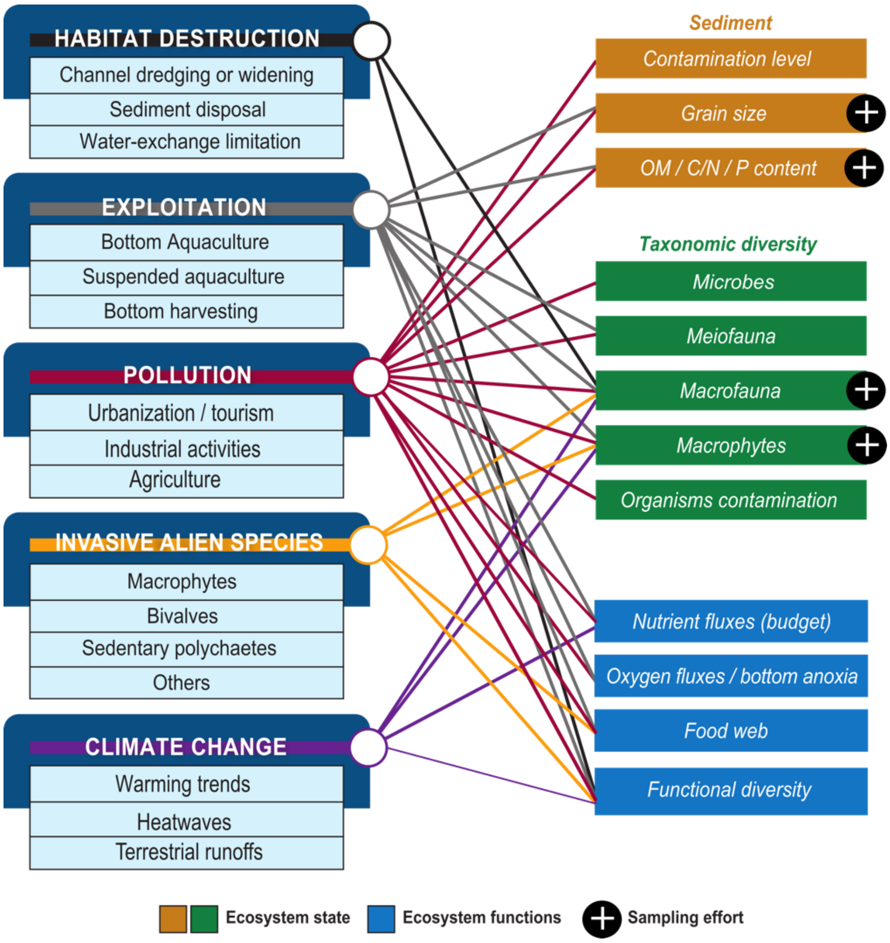

Figure 2. Synthesis of pressures identified at the scale of Mediterranean coastal lagoons and the studied responses of the benthic system. Sampling effort concerns the compartments monitored under the European Water Framework Directive. OM: organic matter, C: carbon, N: nitrogen, P: phosphorous

Table 1. List of reviewed studies investigating the direct impacts of the five main anthropogenic pressures on the soft-bottom benthic compartment, published between 2000 and 2022. Studies that investigated ecological impacts and characterized sediment composition or toxicity at the same time are in **bold** (not rewritten in the sediment column). Benthic processes include direct measurements of e.g. bioturbation, benthic fluxes. Studies providing information on the *toxicity of sediments and **contamination of organisms.

Pressures	**Sediment composition or toxicity*** ***- studies that only focused on this issue-***	**Organism diversity or contamination****				**Ecosystem functions**		
		Microbes	**Meiofauna**	**Macrofauna**	**Macrophytes**	**Ecological groups or Functional diversity**	**Benthic processes**	**Food web**
Habitat destruction (7)				**Bettoso et al. 2020** **Como et al. 2007** Khedhri et al. 2015 **Khedhri et al. 2016** Khedhri et al. 2017 Munari & Mistri 2014 **Ponti et al. 2009**		**Bettoso et al. 2020** Khedhri et al. 2015 **Khedhri et al. 2016** Khedhri et al. 2017 Munari & Mistri 2014		
Pollution (35) (micro- and macropollution)	Accornero et al. 2008 Arienzo et al. 2013 Bahroumi et al. 2016* Belluci et al. 2002 Galgani et al. 2009* Leon et al. 2017 Moreno-Gonzales & Leon 2017 Rigaud et al. 2012* Zaaboub et al. 2015*	Ben Salem et al. 2019 **Cibic et al. 2012** **Franzo et al. 2016** **Said et al. 2010** **Saidi et al. 2019**	**Cibic et al. 2012** **Coccioni et al. 2009** Foster et al. 2012 Franzo et al. 2016 **Martins et al. 2016** Orabi et al. 2017 **Ruiz et al. 2012** **Saidi et al. 2019**	Bahroumi et al. 2014** **Carafa et al. 2007**** **Cibic et al. 2012** Como and Magni 2009 Dolbeth et al. 2003 Franzo et al. 2016 **Jones et al. 2022** **Mahé et al. 2021** Marin-Guirao et al. 2005 **Pitacco et al. 2020** **Rigaud et al. 2019**** Telahigue et al. 2022**	Carafa et al. 2007** **Espel et al. 2019** Le Fur et al. 2018, 2019 Marin-Guirao et al. 2005** Pasqualini et al. 2017	**Jones et al. 2022** **Nasi et al. 2018**	**Cibic et al. 2012** Franzo et al. 2016 Rigaud et al. 2021 Zilius et al. 2015	Carlier et al. 2009a
Exploitation (28)	Badino et al. 2004 Sfriso et al. 2003, 2005		Lacoste et al. 2020 **Mahmoudi et al. 2008**	**Castaldelli et al. 2003** **Duport et al. 2007** Lacoste et al. 2020 **Mantovani et al. 2006** Moschino et al. 2011 **Thouzeau et al. 2007**	**Boudouresque et al. 2020**	**Duport et al. 2007** Lacoste et al. 2020 Mantovani et al. 2006	**Anschutz et al. 2007** **Bartoli et al. 2001** **Castaldelli et al. 2003** **Dedieu et al. 2007a,b** **Duport et al. 2007** **Lacoste et al. 2022** **Metzger et al. 2007** Mistri & Munari 2012 Murphy et al. 2018 **Nizzoli et al.2005,**	Carlier et al. 2009b

				2006b, 2007, 2011 Nizzoli et al. 2006a Schmidt et al. 2007 **Thouzeau et al. 2007** **Viaroli et al. 2003**	
Invasive alien species (14)	**Como et al. 2018** Mistri 2003 Munari 2008 Nonnis Marzano et al. 2003 Pranovi et al. 2006 Tlig-Zouari et al. 2011 Mancinelli et al. 2013	Nonnis Marzano et al. 2003 Sfriso et al. 2012 Streftaris & Zenetos 2006	Munari 2008 Tlig-Zouari et al. 2011	Pranovi et al. 2006 Sfriso et al. 2020 Streftaris & Zenetos 2006	Carrozo et al. 2014 **Como et al. 2018** Mancinelli et al. 2013, 2017 Marchessaux et al. 2021a,b
Climate change (9)	Canu et al. 2010 Ghezzo et al. 2018 Munari 2011 Mercurio et al. 2021	Lloret et al. 2008 Derolez et al.2020	Munari 2011 Pitacco et al. 2018	Harzallah & Chapelle 2002 Magri et al. 2020 Derolez et al. 2020	