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► **To cite this version:**

Élise Lacoste, Auriane Jones, Myriam Callier, Judith Klein, Franck Lagarde, et al.. A Review of Knowledge on the Impacts of Multiple Anthropogenic Pressures on the Soft-Bottom Benthic Ecosystem in Mediterranean Coastal Lagoons. *Estuaries and Coasts*, 2023, 10.1007/s12237-023-01188-9 . hal-04053389

HAL Id: hal-04053389

<https://hal.science/hal-04053389v1>

Submitted on 31 Mar 2023

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

3

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12

13 **Abstract**

14 Mediterranean coastal lagoons provide important ecological functions and nature's contribution
15 to people, but they are particularly vulnerable to multiple pressures due to their location at the
16 land-sea interface and the many activities they host. Numerous research and monitoring
17 programs have been conducted to study the functioning of Mediterranean coastal lagoons and
18 to improve their ecological and chemical status, especially since the 2000s with the EU Water
19 Framework Directive. However, many coastal lagoons still had not achieved a good ecological
20 status by 2018. The soft-bottom benthic ecosystem plays a crucial role in the functioning of
21 shallow coastal lagoons, regulating among others nutrient and oxygen fluxes, and hosting a
22 high biodiversity. The alteration of this compartment by anthropogenic pressures is therefore a
23 major problem. Through a literature review, this paper aims to summarize information available
24 on the impacts of the five main human-induced pressures – i.e. exploitation of natural resources,
25 habitat destruction, climate change, pollution and alien invasive species – on the soft-bottom
26 benthic ecosystem in Mediterranean coastal lagoons (period 2000-2022), and to identify
27 perspectives for future research that can contribute to the improvement of monitoring programs.
28 Our review shows that resource exploitation and nutrient pollution have been the two most
29 studied pressures whereas research is still underdeveloped on the impacts of climate change,

30 invasive alien species, and contaminants of emerging concern. We also found that the recording
31 and quantification of pressures is still poor, and that their cumulative effect is poorly
32 understood. In terms of indicators, the microbial and microphytobenthic compartments are
33 being overlooked and functional approaches could be strengthened. This review could help
34 scientists realign research on pressures of priority interest and thus better assist stakeholders in
35 managing coastal lagoons in times of global changes.

36

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

39

40 **1. Introduction**

41 There are about 400 coastal lagoons in the Mediterranean, mainly distributed in Italy, Greece,
42 Turkey and France (Cataudella et al. 2015). These highly productive ecosystems ensure major
43 ecological functions (e.g. regulation of matter cycles, biodiversity maintenance), provide
44 valuable nature's contribution to people (Newton et al. 2018; Pérez-Ruzafa et al. 2019) and in
45 many regions, are the focus of socio-economic interests and support regional economies
46 (Newton et al. 2018). However, the high residence time of lagoon waters, fluctuating
47 environmental conditions, and the multiple activities taking place in and near coastal lagoons
48 make them particularly exposed and vulnerable to anthropogenic pressures (Viaroli et al. 2008;
49 Zaldívar et al. 2008; Pérez-Ruzafa et al. 2019), with eutrophication considered for a long time
50 as the main threat (de Jonge and Elliott 2001; Newton et al. 2014). Eutrophication is a naturally
51 occurring process in most lagoons because they function as a sink for nutrient inputs from the
52 sea and the land. However, excessive nutrient loads in catchment areas since the 1960s has
53 resulted in rates of primary production exceeding rates of mineralization, leading to organic
54 matter accumulation and recurrent and persistent periods of oxygen deficiency (Cloern 2001).
55 These “dystrophic crises” promote nutrient fluxes from the sediment to the water column

56 (Rysgaard et al. 1996; Souchu et al. 1998), which can be associated with the release of toxic
57 compounds such as sulfide (Caumette and Baleux 1980; Castel et al. 1996), and result in mass
58 mortality of benthic macrofauna and fish (Stachowitsch 1992). This issue has been the subject
59 of several research programs in the 1980s and 1990s both at the European scale (e.g. CLEAN:
60 Coastal lagoons and anaerobic processes (Caumette et al. 1996), ROBUST: The ROle of
61 BUffering capacities in STabilising coastal lagoon ecosystems (de Wit et al. 2001), EUMAC:
62 Eutrophication and benthic Macrophytes (Schramm 1999)) and at the regional scale (e.g.
63 Trousselier and Deslous-Paoli 2001), which have laid the foundation for understanding, among
64 others, the prominent role of the benthic ecosystem in the trophic functioning of coastal
65 lagoons. These studies have also served as a reference for the establishment of various
66 monitoring programs such as the European Water Framework Directive (WFD). This
67 management plan was implemented in the 2000s in Europe to achieve the good ecological and
68 chemical status of water bodies, mainly degraded by pollution from urban waste water and
69 agriculture causing eutrophication. This has led to significant efforts to reduce nutrient inputs
70 into water bodies categorized as "transitional waters" by the WFD, allowing the progressive
71 restoration of several coastal lagoons (Le Fur 2018; Derolez et al. 2020). Nonetheless, 60% of
72 transitional waters had still not achieved a good or high ecological status by 2018, especially in
73 Italy (Kristensen et al. 2018).

74 In addition to eutrophication, multiple anthropogenic pressures have emerged, including those
75 associated with climate change such as warming, acidification or hypersalinization. The
76 Millennium Ecosystem Assessment (MEA 2005), and more recently the Intergovernmental
77 Science Policy Platform on Biodiversity and Ecosystem Services (IPBES 2019), defined five
78 main human-induced drivers – also referred to as pressures – that directly and unequivocally
79 influence ecosystem biodiversity and associated nature's contribution to people:
80 overexploitation of natural resources, habitat destruction, human-driven climate change,

81 pollution (i.e. macropollutants related to eutrophication and micropollutants related to chemical
82 contaminants) and invasive alien species. These pressures have been identified as the main
83 threats in the Mediterranean Sea (Coll et al. 2010) and for semi-enclosed coastal systems in
84 Europe (Newton et al. 2014), and their importance is increasingly recognized in the WFD
85 (Cardoso and Free 2008; von der Ohe et al. 2011; Quevauviller 2011). In Europe, although
86 many assessment methods have been developed and intercalibrated, not all pressures have been
87 addressed and indicators cannot, in most cases, diagnose the cause(s) of coastal lagoon
88 ecological degradation (Poikane et al. 2020). The same observation applies to North Africa for
89 which information is diffuse and heterogeneous (El Mahradi et al. 2020). Consequently, better
90 understanding the underlying drivers of Mediterranean coastal lagoons degradation is crucial if
91 we are to manage these ecosystems more effectively.

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

105 basis, we then discuss research gaps and how management should realign with multiple
106 pressures in times of global change.

107

108 **2. Literature review on the impacts of five anthropogenic pressures on the soft-bottom** 109 **ecosystem of Mediterranean Coastal lagoons**

110

111 **2.1. Habitat destruction**

112 Mediterranean coastal lagoons are threatened by engineering works that mainly involve land
113 claim and sand filling for coastal uses (e.g. ports, marinas, urbanizations), bottom dredging for
114 sand extraction, channel creation or beach conditioning, and inlet enlargement or closure to
115 control lagoon-sea exchanges (Pérez-Ruzafa et al. 2019). These engineering works can alter
116 geomorphology, sediment transport, seafloor integrity and hydrodynamics and lead to habitat
117 loss (Newton et al. 2014). Specifically, dredging may cause many negative effects on the
118 benthic compartment, according to Quigley and Hall (1999) and Miller et al. (2002), mainly by
119 1/ changing sediment property, 2/ re-suspending fine sediment and releasing porewater, which
120 can lead to nutrient and/or contaminant pollution and to hypoxic events, 3/ reducing benthic
121 macrofauna richness and abundance, including sometimes complete community loss.

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

129 abundance of some species (*Streblospio shrubsolii* and *Corophium insidiosum*) (Ponti et al.
130 2009), or changes in the trophic structure (Khedri et al. 2015).

131 Three publications used the BACI approach (Before/After Control/impact), authorizing a
132 robust comparison of sampling sites (Bettoso et al. 2020; Munari and Mistri 2014; Ponti et al.
133 2009). Five publications used benthic descriptors to assess the impact of habitat destruction on
134 macrofauna (Table S1), based on trophic groups and on indices calculated for WFD diagnoses
135 (AMBI, BENTIX, M-AMBI, TUBI, BITS) (Munari and Mistri 2014; Khedri et al. 2015, 2016,
136 2017; Bettoso et al. 2020). Out of these five publications, only two included yearly monitoring
137 (Table S1), and showed significant negative impacts of habitat modifications on macrofauna
138 taxonomic diversity and ecological indices, which had recovered in a year or less (3-6 months
139 (Bettoso et al. 2020) and 1 year (Munari and Mistri 2014)).

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

146 147 **2.2. Pollution**

148 Eutrophication remains a major environmental issue, aggravated by the current trend of rising
149 temperatures and more frequent torrential rains due to climate change. In the past few years,
150 several studies have described drastic changes of the benthic compartment linked to
151 eutrophication, such as changes in the distribution patterns of macrophytes (Le Fur et al. 2018)
152 or reduction in macrofauna richness and diversity (Jones et al. 2022 PREPRINT) at the scale
153 of French Mediterranean lagoons. Other studies focused on the effects associated, in particular
154 recurrent and persistent periods of hypoxia and anoxia - known as dystrophic crises - which

155 include the modification of oxygen and nutrient fluxes at the sediment-water interface (Zilius
156 et al. 2015; Rigaud et al. 2021), seagrass mortality (Viaroli et al. 2008), and changes in
157 macrofauna community structure (Dolbeth et al. 2003) with death of organisms like *Polydora*
158 *ciliata* (Como and Magni 2009) or *Ruditapes philippinarum* (Mahé et al. 2021). Eutrophication
159 may also modify food web structure and functioning as shown by Carlier et al. (2009a) who
160 observed marked differences in $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of food sources and consumers between the
161 lagoons of Canet and La Palme in France. Following the implementation of the WFD and the
162 reduction of urban nutrient inputs, several studies described the restoration trajectories taking
163 place in coastal lagoons, also referred to as oligotrophication, with an apparently strong
164 hysteresis (Pasqualini et al. 2017; Le Fur 2018; De Wit et al. 2020). Recovery trajectory of the
165 macrophyte community in 21 French Mediterranean coastal lagoons occurred with regime
166 shifts, and a full recovery from highly eutrophic to oligotrophic conditions may require more
167 than a decade (Le Fur et al. 2019). More generally, the full recovery of coastal and estuarine
168 benthic ecosystems from long-term degradation can take a minimum of 15-25 years (Borja et
169 al. 2010).

170 Other common pollutions (i.e. micropollutions) reported for Mediterranean coastal lagoons are
171 trace metals from mining and industrial activities (e.g. Marín-Guirao et al. 2005; Ruiz et al.
172 2012; Martins et al. 2016), and historical contaminants such as polycyclic aromatic
173 hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and organochlorinated pesticides
174 (OCPs) from industrial and agricultural effluents (e.g. Cibic et al. 2012; León et al. 2017; Ben
175 Salem et al. 2019). All these pollutants are mainly brought by rivers, meaning that flash flood
176 events may have a significant impact on sediment contamination (León et al. 2017; Moreno-
177 González and León 2017). These pollutions have a significant impact on benthic species such
178 as the mussel *Mytilus galloprovincialis* (Barhoumi et al. 2014) or the clam *R. philippinarum*
179 (Carafa et al. 2007) which both show high bioaccumulation rates. The seagrass *Cymodocea*

180 *nodosa* and the seaweed *Ulva rigida* have also been shown to accumulate trace metals and
181 herbicides (Marín-Guirao et al. 2005; Carafa et al. 2007), and the occurrence of abnormalities
182 in foraminiferal tests has been correlated to trace metal pollution (Coccioni et al. 2009). At a
183 higher level of biological organization, pollution affects the composition and distribution of
184 benthic communities. The abundance of tolerant species such as the foraminifera
185 *Quinqueloculina bicostata* has been shown to increase in association with metal pollution
186 (Foster et al. 2012), and the bacterial community composition has been linked with PAHs
187 concentration in the Bizerte lagoon (Ben Salem et al. 2019). Macrofauna, characterized by
188 univariate diversity indices (e.g. species richness, Shannon) or by the biotic indices AMBI and
189 M-AMBI, showed a weak response to chemical contamination (Marin-Guirao et al. 2005;
190 Pitacco et al. 2020) while herbicides and trace metals may have played a role in the decline of
191 seagrass beds observed in a French lagoon (Espel et al. 2019). Finally, our review reveals the
192 lack of studies on the ecosystem level effect of pollution (both macro- and micro-pollution).
193 We found only 3 studies that investigated the effect of micropollution on functional processes.
194 In an integrated study, no taxonomic but functional differences of microbial communities was
195 shown along a gradient of hydrocarbon pollution in a riverine lagoonal system where
196 contaminated sediment hosted an extremely active microbial community compared with
197 unpolluted sites (Cibic et al. 2012). Conversely, an inhibition of microbial processes (as a proxy
198 of ecosystem functioning) was observed along a gradient of contamination in the Mar Piccolo
199 of Taranto (Franzo et al. 2016). Another study took a first step in studying ecosystem
200 functionality through biological trait analysis of polychaetes associated with contamination
201 (Nasi et al. 2018). This finding of a lack of functional approach is in line with a recent French
202 national expert report that highlights the lack of studies on the effects of pesticides in the marine
203 environment at the ecosystem level (Leenhardt et al. 2022).

204

205 **2.3. Exploitation**

206 Over the last 20 years (28 reviewed papers, Table 1), the effects of aquaculture on benthic
207 ecosystems were studied in different Mediterranean coastal lagoons in Italy (Venice, Marinetta
208 and Sacca di Goro), in France (Thau and Salses Leucate) or in Tunisia (Bizerte). Among these
209 lagoons, some are particularly exploited, such as Thau with 20% of the surface dedicated to
210 oyster and mussel production (*Magallana gigas*, 6 110 T/year ; *Mytilus galloprovincialis*, 2 385
211 T/ year in 2019), and Sacca di Goro with 35% of the surface exploited for clam production
212 (*Ruditapes philipinarum*, 6 000 T/year). Shellfish farming may affect lagoon benthic
213 ecosystems through different processes that have been extensively reviewed worldwide
214 (Gallardi 2014; Lacoste and Gaertner-Mazouni 2015; Lacoste et al. 2020; Boudouresque et al.
215 2020).

216 In Mediterranean coastal lagoons, several studies showed impacts of aquaculture on physical
217 processes (e.g., sedimentation, erosion) and sediment composition. This has been particularly
218 studied in the Venice lagoon, where intensive harvesting of the non-native bivalve Manila clam
219 *R. philippinarum* has resulted in the loss of fine sediment through resuspension (Pranovi et al.
220 1998, 2004). The increase in resuspension of the top layer of sediment caused by the mechanical
221 harvesting of clam (locally known as the “rusca” method) has been shown to bring the anoxic
222 layer close to the bottom, with potential impacts on biogeochemical cycles and on the short-
223 term recolonization by benthic organisms (Badino et al. 2004). Sfriso et al. (2005) confirmed
224 that clam harvesting has significantly contributed to increase sediment resuspension and
225 homogenize surface sediment granulometry and dry density.

226 A second group of studies showed impacts of aquaculture on benthic organisms at the
227 individual level (e.g. physiological performance of *R. philippinarum*, Moschino et al. 2011),
228 but the majority revealed contrasting results regarding the effects at the community level,
229 focusing either on meiofauna (Mahmoudi et al. 2008; Lacoste et al. 2020), macrofauna

230 (Castaldelli et al. 2003; Mantovani et al. 2006; Duport et al. 2007; Lacoste et al. 2020, 2022)
231 or macrophytes such as seagrass meadows (*Cymodocea nodosa*, *Zostera* spp., Boudouresque et
232 al. 2020). In Bizerta lagoon, mussel biodeposition led to modifications of the abundance and
233 diversity of free-living nematodes that could lead to food limitation for their predators and
234 ultimately alter the entire benthic community and ecosystem (Mahmoudi et al. 2008).
235 Conversely, little or no effect of clam harvesting has been detected on macrofauna taxonomic
236 and functional composition (Castaldelli et al. 2003; Mantovani et al. 2006). No impact of
237 shellfish farming has been shown on isotopic values of macrofauna (Carlier et al. 2009b).
238 Finally, many studies looked at the effect of shellfish farming on ecosystem functioning. A
239 majority of studies determined spatial and/or temporal variations of biogeochemical fluxes at
240 the sediment water interface, including measures of the vertical distribution of oxygen and of
241 oxygen fluxes (e.g. Viaroli et al. 2003; Nizzoli et al. 2005; Dedieu et al. 2007), CO₂ fluxes
242 (Bartoli et al. 2001), CaCO₃ and CO₂ production/sequestration (Mistri and Munari 2012),
243 nitrogen and phosphorus fluxes (e.g. Bartoli et al. 2001; Nizzoli et al. 2005; Lacoste et al. 2022),
244 phosphorus diagenesis (Anschutz et al. 2007), vertical distributions of dissolved sodium,
245 potassium, magnesium, calcium (Metzger et al. 2007), acid volatile sulphide, chromium
246 reducible sulphur and labile amorphous iron (Viaroli et al. 2003). Mussel farming and bottom
247 clam culture may create “hotspots” of nutrient fluxes with annual N and P regeneration rates
248 being 4.9 and 13.5 (mussel) and 4.5 and 14.9 (clams) fold greater than those of unfarmed control
249 sediments (Nizzoli et al. 2011). Finally, Schmidt et al. (2007) showed the importance of oysters
250 biodeposition on bioturbation in the Thau lagoon.

251

252 **2.4. Invasive alien species**

253 Coastal lagoons are considered to be key entry points for the arrival of new alien species in the
254 Mediterranean Sea, with the Venice and Thau lagoons as prime examples (Boudouresque et al.

255 2010; Marchini et al. 2015). Indeed, coastal lagoons are often home to important cultures of
256 non-native shellfish species (e.g. *M. gigas*, *R. philippinarum*). For example, the import of non-
257 native oysters (seed and older individuals) has in many cases served as a vector for other alien
258 species, mainly their epibiota and parasites, such as macroalgae (e.g. *Undaria pinnatifida*) and
259 invertebrates (e.g. *Myicola ostreae*), which in turn have the potential of becoming invasive
260 (Marchini et al. 2015). Furthermore, shipping traffic of commercial ships and recreational
261 boats, another potential vector for alien species invasion, is intense close to and inside coastal
262 lagoons.

263 Despite the numerous alien species recorded in Mediterranean coastal lagoons (55 established
264 alien species in Venice lagoon by 2014 (Marchini et al. 2015) and 50 alien macrophyte species
265 by 2009 in the Thau lagoon (Boudouresque et al. 2010), their effect on the benthic compartment
266 seems to have been neglected. Indeed, our literature survey identified only 14 articles, for the
267 considered period, that investigated the effect of alien species on soft-bottom benthic organisms
268 and/or benthic ecosystem functioning, or that summarized older literature on the subject (Sfriso
269 et al. 2020; Streftaris and Zenetos 2006). Only one study investigated the effect of invasive
270 alien species on the sediment structure of lagoons and recorded no significant effect of the
271 mussel *Arcuatula senhousia* on sediment features in the Oristano lagoon-gulf system (Western
272 Sardinia) (Como et al. 2018). As far as benthic assemblage structure and composition was
273 concerned, other studies focused on the effect of invasive alien macroinvertebrate on
274 macrofauna diversity, or of invasive alien macrophyte on macrophyte diversity with just one
275 investigating the effect of an invasive alien macrophyte on macrofauna (Nonnis Marzano et al.
276 2003). Sampling designs employed were largely spatial comparisons (control vs impact) and
277 only a few took into account time (pre-invasion vs post-invasion) (Table S1). Overall, all except
278 one reported significant changes in community composition with four also reporting changes
279 in community structure (taxonomic distinctiveness, richness, and evenness) (Pranovi et al.

280 2006; Streftaris and Zenetos 2006; Munari 2008; Sfriso et al. 2012). Most studies were
281 conducted in Italian lagoons and dealt with the following invasive alien species: the tube-
282 building worm *Ficopomatus enigmaticus* (Lesina lagoon, Italy, Nonnis Marzano et al. 2003),
283 the bivalve *Anadara inaequalis* (Venice lagoon, Ambrogi 2000), the Asian mussel *A.*
284 *senhousia* (Sacca di Goro lagoon, Mistri 2003; Munari 2008), the pearl oyster *Pinctada radiata*
285 (Bizerte lagoon, Tlig-Zouari et al. 2011), the Manila clam *R. philippinarum* (Venice lagoon,
286 Pranovi et al. 2006), the macroalgae *Agarophyton vermiculophyllum* (lagoons of Sacca di Goro
287 and Pialassa della Baiona, Sfriso et al. 2012) and *Valonia aegagropila* (Lesina lagoon, Nonnis
288 Marzano et al. 2003).

289 In terms of functional approaches, few studies investigated the effect of invasive alien species
290 on trophic interactions and only three species have been considered: the mussel *A. senhousia*
291 (Como et al. 2018), the blue crab *Callinectes sapidus* (Mancinelli et al. 2013; Carrozzo et al.
292 2014; Mancinelli et al. 2017) and the ctenophore *Mnemiopsis leidyi* (Marchessaux et al.
293 2021a,b). Five out of six studies revealed significant effects of invasive alien species on benthic
294 communities through trophic competition and predation by using bulk carbon and nitrogen
295 stable isotopes and gut content analyses (Mancinelli et al. 2013; Carrozzo et al. 2014;
296 Mancinelli et al. 2017; Marchessaux et al. 2021a,b). On the level of ecosystem functioning, six
297 studies found effects of invasive species on benthic-pelagic coupling and anoxia or suspected
298 such effects. Between 1990 and 1999, the spread of the benthic Manila clam *R. philippinarum*
299 changed the functioning of the Venice lagoon due to its relatively high clearance rate which
300 greatly increased the macrobenthic filtration capacity (Pranovi et al. 2006). In the Berre lagoon
301 (South of France), the pelagic ctenophore *M. leidyi*, which preys on benthic organisms probably
302 plays an underestimated role in the transfer of benthic organic matter into the pelagic food web
303 (Marchessaux et al. 2021a,b). Lastly, the invasive macrophyte species *Laminaria japonica* in
304 the Thau lagoon (Streftaris and Zenetos 2006) and *V. aegagropila* in the Lesina lagoon (Nonnis

305 Marzano et al. 2003) were both reported to cause local anoxia whereas *A. vermiculophyllum*
306 decreased the risk of summer anoxia in the Venice lagoon (Sfriso et al. 2020).

307

308 **2.5. Climate change**

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

324 The increasing frequency and intensity of summer thermal anomalies associated with
325 hypersalinity, and the potentially associated anoxic crises are likely to become a major threat
326 to macrobenthic communities in transitional environments (Pitacco et al. 2018; Mercurio et al.
327 2021). For example, the 2003 summer heatwave in the Comacchio saltworks (Italy) reduced
328 the species richness of the macrofauna community which shifted from mollusc- to annelida-
329 dominated (Munari 2011; Pitacco et al. 2018). Exploited natural resources such as the Manila

330 clam *R. philippinarum* could also be impacted by climate change with consequences for the
331 sustainability of aquaculture (Canu et al. 2010; Ghezzi et al. 2018).

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

339

340 **2.6. Cumulative pressures**

341 While pressures may occur in isolation, 97.7% of the ocean is currently affected by more than
342 one pressure (Halpern et al. 2015), and coastal regions have been shown to be the most
343 threatened by cumulative pressures in the Mediterranean (Coll et al. 2010; Micheli et al. 2013;
344 Korpinen et al. 2021). In many studies however, only the presence or absence of a unique driver
345 is considered whereas cumulative impacts are increasingly obvious, as it is the case for
346 eutrophication and climatic extreme events. In a lab experiment simulating the Mar Menor
347 lagoon conditions, warming and nitrogen:phosphorus ratio (whose level depends on inputs from
348 the watershed and internal regeneration) have been shown to modify the population of an
349 epiphytic diatom (Belando et al. 2019). Still in the Mar Menor, the progressive increase in
350 nutrient loads and resulting algal blooms, combined with an extreme rainfall event, led to the
351 complete extinction of the bivalve *Pina nobilis* in the deeper part of the lagoon (Nebot-Colomer
352 et al. 2021). Changes in the local environmental conditions may also have favored the intrusion
353 of a new pathogen, adding extra pressure on the already weakened population of *P. nobilis*
354 (Nebot-Colomer et al. 2021). In the Lesina lagoon, an artificial change in the hydrological
355 regime (temporary closure of a tidal channel) combined with unusual meteorological

356 parameters has been shown to cause a dystrophic crisis, accompanied by a shift from a
357 macrophyte-based system to a phytoplankton-based system in the isolated area (Vignes et al.
358 2009). Finally, in conjunction with new pathogens and/or chemicals, the increasing frequency
359 of extreme meteorological events in the Mediterranean region (Kysely et al. 2012; Cramer et
360 al. 2018) could also cause climate-induced toxicant sensitivity responses in some species, as
361 shown for the bivalves *R. philippinarum* and *Mytilus galloprovincialis* exposed to caffeine and
362 heatwaves (De Marchi et al. 2022).

363 Overall, with only a few studies to date focusing on cumulative impacts in the marine realm,
364 which showed idiosyncratic responses (Gissi et al. 2021), it appears that the nature of the
365 interactions between pressures is largely unpredictable (Côté et al. 2016; Carrier-Belleau et al.
366 2021), and that further work should be encouraged to enable general conclusions to be drawn.

367

368 **3. Perspectives for future research and monitoring programs on soft-bottom benthic** 369 **ecosystem in Mediterranean coastal lagoons**

370

371 **3.1. Realign research with pressures of emerging concern**

372 Among the studies reviewed, exploitation and pollution have been the two most studied human-
373 induced pressures in Mediterranean coastal lagoons so far (Table 1, Fig. 2). Eutrophication has
374 been the focus of much research since the 1980s, complemented in the 2000s by regulatory
375 monitoring of European ecosystems through the WFD. Compared to this, the emerging
376 pressures formalized in the 2000s by the MEA suffer from a lack of research as illustrated by
377 the small number of studies identified in our review concerning climate change (Table 1).
378 Worldwide, the impact of extreme events on benthic communities in coastal lagoons has been
379 the focus of less than 40 studies (Durreau et al. 2021). Ecosystem monitoring and management
380 is therefore focused on the provision of ecosystem functions and services under current

381 environmental conditions, yet this could rapidly lead to inappropriate management guidance
382 and undervaluation of the importance of human impacts on biodiversity. Research on
383 biodiversity loss must therefore realign with emerging issues to match predicted impact severity
384 and better guide management actions (Mazor et al. 2018). In addition to climate change, we
385 call for further research on the issues of invasive alien species and contaminants of emerging
386 concern. Our review emphasizes that although a lot of research has inventoried the presence of
387 invasive alien species in Mediterranean coastal lagoons, the quantification of the role of these
388 species on benthic biodiversity and ecosystem functioning is in its infancy. Functional impacts
389 of invasive alien species on the environment they colonize are hard to qualify and quantify but
390 efforts should be made in this domain to anticipate negative and cascading impacts at the
391 ecosystem level (Dethier and Hacker 2004). As an example, the invasive benthic suspension
392 feeder *Crepidula fornicata* has been shown to strongly influence important ecological processes
393 such as the coastal ‘silicate pump’ or carbon cycling in the Bay of Brest (Ragueneau et al. 2005;
394 Martin et al. 2007). As another priority, we identified the need to monitor the distribution and
395 fate of newly-detected contaminants in sediments, as this compartment represents a major
396 reservoir of pollution, and to better evaluate their impact at the community and ecosystem level.
397 Contaminants of emerging concern such as antibiotics, sun creams and nano/microplastics are
398 still overlooked at the moment despite being a particular issue in marine and transitional waters
399 (e.g. Anbumani and Kakkar 2018; Fastelli and Renzi 2019; Renzi et al. 2020) where they are
400 likely to be brought in significant amounts by aquaculture, shipping/sailing or other recreational
401 activities. Although the research collected in our review shows that contaminants from diverse
402 origins may have a significant impact on all the biological components of the sediment, most
403 of them are still unregulated and the effects they can produce may be missed or overlooked in
404 many monitoring and surveillance programs such as the WFD (Fig. 2).

405 For a comprehensive understanding of ecosystem modifications linked to anthropogenic
406 pressures in Mediterranean coastal lagoons, a necessary step is to quantify the exposure of
407 lagoons to the identified pressures more precisely and on a regular basis. A common framework
408 for the description and quantification of the multiple anthropogenic pressures in Mediterranean
409 coastal lagoons is lacking, and efforts remain fragmented, relying mainly on semi-quantitative
410 assessments or expert judgments (Borja et al. 2011; Orfanidis et al. 2014). In the French
411 Mediterranean, the quantification of multiple pressures for 25 coastal lagoons dates back to
412 2013 (Derolez et al. 2014). In Greece and North Africa, pressure quantification is only recently
413 available for a few study sites (Maneas et al. 2019; Bray et al. 2022; El Kateb et al. 2018; El
414 Mahrad 2020). Recent studies based on Geographic Information System analyses (Morant et
415 al. 2021) assessing pollution and hydro-morphological pressures in coastal lagoons are
416 promising and should be updated regularly and made available to stakeholders. Some initiatives
417 could serve as a basis to facilitate data gathering by assembling, organizing and sharing
418 environmental knowledge among the Mediterranean, like the open-data platform MEDTRIX
419 (<https://medtrix.fr/>), which makes available results from the WFD monitoring and the
420 contamination of French coastal waters.

421

422 **3.2. Finding suitable indicators for monitoring to detect anthropogenic pressures**

423 Today, when most assessment methods (i.e. indicators) in European transitional waters are
424 reported to be responding to eutrophication or organic pollution, other pressures such as toxic
425 pollution, hydro-morphological modifications or acidification received significantly less efforts
426 (Poikane et al. 2020). More general concerns have been raised that not all pressures are
427 addressed adequately by the assessment methods currently in use (Reyjol et al. 2014). Although
428 Borja et al. (2011, 2015) have shown that several marine and estuarine benthic quality
429 assessment indices, such as the M-AMBI for macrofauna, have significant correlations with

430 human pressures (e.g. eutrophication, organic enrichment, harbours), other studies showed that
431 these indices used in the WFD context have difficulties detecting pressures when applied in a
432 generalized way across coastal lagoons (Munari and Mistri 2008; Simboura and Reizopoulou
433 2008; García-Sánchez et al. 2012; Jones et al. 2022 *preprint*). Basic scientific research is
434 continuously needed to propose the use of new descriptors and develop smart and easy-to-use
435 indicators that do not require high sampling and analytical efforts (Bonometto et al. 2022).

436 It also appears that the WFD is missing key components in the assessment of soft-bottom
437 benthic ecosystems such as microbes, microphytobenthos and meiofauna (Fig. 2), whereas
438 several studies showed their usefulness in detecting changes associated with human pressures.

439 Although there are still some limitations in their routine use, nematodes (main group of
440 meiofauna) provide elements to assess the ecological quality status of Mediterranean coastal
441 ecosystems through specific indicators (Moreno et al. 2011; Semprucci et al. 2015).

442 Collaborative work between African and European researchers to enrich sequence databases
443 (DNA barcoding, NGS), in conjunction with morphotaxonomy (Boufahja et al. 2015), could be
444 part of the solution to progress in the description of nematode diversity in the Mediterranean
445 region and use them as models to evaluate lagoon ecosystem status in the face of global
446 changes. Microbes (bacteria, archaea, and protists) are also seldom used as bioindicators in
447 routine assessments (Table 1, Fig. 2) although they have been recognized for their importance
448 in benthic diversity and functioning. Metagenomic and metatranscriptomic are promising tools
449 that could help to predict community functional changes under different environmental and
450 anthropogenic pressures. However, few works are currently available and further manipulative
451 studies targeting the effects of individual and multiple pressures on aquatic microbial
452 communities should be conducted to evaluate their possible integration in biomonitoring
453 programs.

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

473

474 **3.3. Improve and harmonize sampling design in research and monitoring**

475 Comparison of research studies dealing with environmental impacts in coastal lagoons is
476 challenging due to the high spatio-temporal variability between lagoons and lack of
477 homogeneous approaches (Table S1). The studies show contrasting results and differ across the
478 lagoon studied, the identity and intensity of the pressures (e.g. contaminant levels, density of

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

504 strategic design of monitoring networks, to harmonize best practice in addressing these different
505 issues.

506

507 **Conclusion**

508 The soft-bottom benthic compartment is crucial in the functioning of coastal lagoon ecosystems
509 which have been the focus of much research since the 1980s in the eutrophication context. We
510 reviewed the currently studied impacts of five major anthropogenic drivers of biodiversity loss
511 on soft-bottom benthic ecosystems of Mediterranean lagoons, and identified uneven efforts to
512 address them. Overall, the impacts of invasive alien species and emerging chemical
513 contaminants are particularly overlooked, as well as the effects of climate change which may
514 exacerbate the already existing pressures. The impacts in terms of ecosystem functioning were
515 also weakly addressed. The long-term monitoring of water bodies implemented in e.g., the EU
516 WFD, has provided valuable information on the ecological status trajectories of many coastal
517 lagoons. However, in the face of multiple and cumulative pressures, it is time to gain new
518 knowledge and to reinforce monitoring programs to be sure to capture the complexity of the
519 undergoing changes. Such effort is important because Mediterranean coastal lagoons are
520 ecologically valuable and provide many nature's contributions to people.

521

522 **Acknowledgements:**

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

526

527

528 **Bibliography**

- 529 Accornero, A., R. Gnerre, and L. Manfra. 2008. Sediment concentrations of trace metals in the Berre lagoon
530 (France): An assessment of contamination. *Archives of Environmental Contamination and Toxicology* 54: 372–
531 385.
- 532 Ambrogi, A.O., 2000. Biotic invasions in a Mediterranean Lagoon. *Biol Invasions* 2, 165–176.
533 <https://doi.org/10.1023/A:1010004926405>
- 534 Anbumani, S., and P. Kakkar. 2018. Ecotoxicological effects of microplastics on biota: a review. *Environmental*
535 *Science and Pollution Research*. Springer.
- 536 Anschutz, P., G. Chaillou, and P. Lecroart. 2007. Phosphorus diagenesis in sediment of the Thau Lagoon.
537 *Estuarine, Coastal and Shelf Science* 72: 447–456.
- 538 Arienzo, M., A. Masuccio, and L. Ferrara. 2013. Evaluation of sediment contamination by heavy metals,
539 organochlorinated pesticides, and polycyclic aromatic hydrocarbons in the Berre coastal lagoon (Southeast
540 France). *Archives of Environmental Contamination and Toxicology* 65: 396–406.
- 541 Badino, G., F. Bona, A. Maffiotti, O. Giovanardi, and F. Pranovi. 2004. Impact of mechanical clam harvesting on
542 a benthic habitat: Evaluation by means of sediment profile imaging. *Aquatic Conservation: Marine and*
543 *Freshwater Ecosystems* 14.
- 544 Barhoumi, B., A. Elbarhoumi, C. Clérandeau, A. M. Al-Rawabdeh, A. Atyaoui, S. Touil, M. R. Driss, and J.
545 Cachot. 2016. Using an Integrated Approach to Assess the Sediment Quality of a Mediterranean Lagoon, the
546 Bizerte Lagoon (Tunisia). *Ecotoxicology* 25. Springer New York LLC: 1082–1104.
- 547 Barhoumi, B., K. Le Menach, C. Clérandeau, W. Ben Ameer, H. Budzinski, M. R. Driss, and J. Ô. Cachot. 2014.
548 Assessment of pollution in the Bizerte lagoon (Tunisia) by the combined use of chemical and biochemical
549 markers in mussels, *Mytilus galloprovincialis*. *Marine Pollution Bulletin* 84: 379–390.
- 550 Bartoli, M., D. Nizzoli, P. Viaroli, E. Turolla, G. Castaldelli, E. A. Fano, and R. Rossi. 2001. Impact of *Tapes*
551 *philippinarum* farming on nutrient dynamics and benthic respiration in the Sacca di Goro. *Hydrobiologia* 455:
552 203–212.
- 553 Belando, M. D., Martínez, P. M., Aboal, M. (2019). Interactive effects of warming and eutrophication on
554 population dynamics and stalk production of epiphytic diatoms in transitional waters. *Estuarine, Coastal and*
555 *Shelf Science*, 229(May), 106413. <https://doi.org/10.1016/j.ecss.2019.106413>
- 556 Bellucci, L. G., M. Frignani, D. Paolucci, and M. Ravanelli. 2002. Distribution of heavy metals in sediments of
557 the Venice Lagoon: The role of the industrial area. *Science of the Total Environment* 295: 35–49.
- 558 Bettoso, N., I. F. Aleffi, L. Faresi, A. D'Aietti, and A. Acquavita. 2020. Macrozoobenthos monitoring in relation
559 to dredged sediment disposal: The case of the Marano and Grado Lagoon (northern Adriatic Sea, Italy).
560 *Regional Studies in Marine Science* 33: 100916.
- 561 Bonometto, A., E. Ponis, F. Cacciatore, E. Riccardi, S. Pigozzi, P. Parati, M. Novello, et al. 2022. A New Multi-
562 Index Method for the Eutrophication Assessment in Transitional Waters: Large-Scale Implementation in
563 Italian Lagoons. *Environments - MDPI* 9.
- 564 Borja, Á., D. M. Dauer, M. Elliott, and C. A. Simenstad. 2010. Medium- and Long-term Recovery of Estuarine
565 and Coastal Ecosystems: Patterns, Rates and Restoration Effectiveness. *Estuaries and Coasts* 33: 1249–1260.
- 566 Borja, A., Barbone, E., Basset, A., Borgersen, G., Brkljacic, M., Elliott, M., Garmendia, J.M., Marques, J.C.,
567 Mazik, K., Muxika, I., Neto, J.M., Norling, K., Rodríguez, J.G., Rosati, I., Rygg, B., Teixeira, H., Trayanova,
568 A., 2011. Response of single benthic metrics and multi-metric methods to anthropogenic pressure gradients,
569 in five distinct European coastal and transitional ecosystems. *Mar Pollut Bull* 62, 499–513.
570 <https://doi.org/10.1016/j.marpolbul.2010.12.009>
- 571 Borja, Á., S. L. Marín, I. Muxika, L. Pino, and J. G. Rodríguez. 2015. Is there a possibility of ranking benthic
572 quality assessment indices to select the most responsive to different human pressures? *Marine Pollution*
573 *Bulletin* 97: 85–94.
- 574 Boudouresque, Charles F., J. Klein, S. Ruitton, and M. Verlaque. 2010. Biological Invasion: The Thau Lagoon, a
575 Japanese Biological Island in the Mediterranean Sea. In *Global Change: Mankind-Marine Environment*
576 *Interactions*, ed. H.-J. Ceccaldi, I. Dekeyser, M. Girault, and G. Stora, 151–156. Springer Netherlands.
- 577 Boudouresque, Charles François, A. Blanfuné, G. Pergent, C. Pergent-Martini, M. Perret-Boudouresque, and T.
578 Thibaut. 2020. Impacts of Marine and Lagoon Aquaculture on Macrophytes in Mediterranean Benthic
579 Ecosystems. *Frontiers in Marine Science* 7: 1–19.
- 580 Boufahja, F., F. Semprucci, H. Beyrem, and P. Bhadury. 2015. Marine Nematode Taxonomy in Africa : Promising
581 Prospects Against Scarcity of Information. *Journal of Nematology* 47: 198–206.
- 582 Bray, L., S. Faulwetter, H. Kaberi, A. P. Karageorgis, E. Kastanidi, N. Katsiaras, A. Pavlidou, et al. 2022.
583 Assessing pressure drivers on the benthic ecosystem in the coastal zone of Western Messinia, Greece.
584 *Estuarine, Coastal and Shelf Science*. Elsevier Ltd: 138954.

- 585 Cabana, D., Sigala, K., Nicolaidou, A., Reizopoulou, S., 2013. Towards the implementation of the Water
586 Framework Directive in Mediterranean transitional waters: the use of macroinvertebrates as biological quality
587 elements. *Adv Oceanogr Limnol* 4, 212–240. <https://doi.org/10.1080/19475721.2013.846279>
- 588 Canu, D. M., P. Camprostrini, S. Dalla Riva, R. Pastres, L. Pizzo, L. Rossetto, and C. Solidoro. 2011. Addressing
589 Sustainability of Clam Farming in the Venice Lagoon. *Ecology and Society* 16.
- 590 Carafa, R., J. Wollgast, E. Canuti, J. Lighthart, S. Dueri, G. Hanke, S. J. Eisenreich, P. Viaroli, and J. M. Zaldívar.
591 2007. Seasonal variations of selected herbicides and related metabolites in water, sediment, seaweed and clams
592 in the Sacca di Goro coastal lagoon (Northern Adriatic). *Chemosphere* 69: 1625–1637.
- 593 Cardoso, A. C., and G. Free. 2008. Incorporating invasive alien species into ecological assessment in the context
594 of the water framework directive. *Aquatic Invasions* 3: 361–366.
- 595 Carlier, A., Riera, P., Amouroux, J.-M., Bodiou, J.-Y., Desmalades, M., & Grémare, A. (2008). Food web
596 structure of two Mediterranean lagoons under varying degree of eutrophication. *Journal of Sea Research*,
597 60(4), 264–275. <https://doi.org/10.1016/j.seares.2008.10.006>
- 598 Carlier, A., P. Riera, J. M. Amouroux, J. Y. Bodiou, M. Desmalades, and A. Gremare. 2009. Spatial heterogeneity
599 in the food web of a heavily modified Mediterranean coastal lagoon: stable isotope evidence. *Aquatic Biology*
600 5: 167–179.
- 601 Carrier-Belleau, C., L. Pascal, C. Nozais, and P. Archambault. 2021. Tipping points and multiple drivers in
602 changing aquatic ecosystems: A review of experimental studies. *Limnology and Oceanography* 9999: 1–19.
- 603 Carrozzo, L., L. Potenza, P. Carlino, M. L. Costantini, L. Rossi, and G. Mancinelli. 2014. Seasonal abundance and
604 trophic position of the Atlantic blue crab *Callinectes sapidus* Rathbun 1896 in a Mediterranean coastal habitat.
605 *Rendiconti Lincei* 25: 201–208.
- 606 Carvalho, L., E. B. Mackay, A. C. Cardoso, A. Baattrup-Pedersen, S. Birk, K. L. Blackstock, G. Borics, et al.
607 2019. Protecting and restoring Europe’s waters: An analysis of the future development needs of the Water
608 Framework Directive. *Science of the Total Environment* 658. Elsevier B.V.: 1228–1238.
- 609 Castaldelli, G., S. Mantovani, D. T. Welsh, R. Rossi, M. Mistri, and E. A. Fano. 2003. Impact of commercial clam
610 harvesting on water column and sediment physicochemical characteristics and macrobenthic community
611 structure in a lagoon (Sacca di Goro) of the Po river Delta. *Chemistry and Ecology* 19: 161–171.
- 612 Castel, J., Caumette, P., Herbert, R., 1996. Eutrophication gradients in coastal lagoons as exemplified by the Bassin
613 d’Arcachon and the Étang du Prévost. *Hydrobiologia* 329. <https://doi.org/10.1007/BF00034542>
- 614 Cataudella, S., D. Crosetti, and F. Massa. 2015. Mediterranean coastal lagoons: sustainable management and
615 interactions among aquaculture, capture fisheries and the environment. General Fisheries Commission for the
616 Mediterranean. Studies and Reviews, (95), I.
- 617 Caumette, P., Baleux, B., 1980. Etude des eaux rouges dues à la prolifération des bactéries photosynthétiques
618 sulfo-oxydantes dans l’étang du Prévost, lagune saumâtre méditerranéenne. *Mar Biol* 56, 183–194.
- 619 Caumette, P., J. Castel, and R. Herbert. 1996. Coastal lagoon eutrophication and anaerobic processes (C.L.E.A.N.):
620 Nitrogen and sulfur cycles and population dynamics in coastal lagoons. A research programme of the
621 environment programme of the E.C. (DG XII). Springer Science & Business Media.
- 622 Cernansky, R. 2017. The biodiversity revolution. *Nature* 546: 22–24.
- 623 Cibic, T., A. Franzo, M. Celussi, C. Fabbro, and P. Del Negro. 2012. Benthic ecosystem functioning in
624 hydrocarbon and heavy-metal contaminated sediments of an Adriatic lagoon. *Marine Ecology Progress Series*
625 458: 69–87.
- 626 Cloern, J.E., 2001. Our evolving conceptual model of the coastal eutrophication problem.
627 *Marine Ecology Progress Series* 210, 223–253.
- 628 Coccioni, R., F. Frontalini, A. Marsili, and D. Mana. 2009. Benthic foraminifera and trace element distribution: A
629 case-study from the heavily polluted lagoon of Venice (Italy). *Marine Pollution Bulletin* 59. Elsevier Ltd: 257–
630 267.
- 631 Coll, M., C. Piroddi, J. Steenbeek, K. Kaschner, F. Ben Rais Lasram, J. Aguzzi, E. Ballesteros, et al. 2010. The
632 Biodiversity of the Mediterranean Sea: Estimates, Patterns, and Threats. Edited by Steven J. Bograd. *PLoS*
633 *ONE* 5: e11842.
- 634 Como, S., P. Magni, D. Casu, A. Floris, G. Giordani, S. Natale, G. A. Fenzi, G. Signa, and G. De Falco. 2007.
635 Sediment characteristics and macrofauna distribution along a human-modified inlet in the Gulf of Oristano
636 (Sardinia, Italy). *Marine Pollution Bulletin* 54: 733–744.
- 637 Como, S, A. Floris, A. Pais, P. Rumolo, S. Saba, M. Sprovieri, and P. Magni. 2018. Assessing the impact of the
638 Asian mussel *Arcuatula senhousia* in the recently invaded Oristano Lagoon-Gulf system (W Sardinia, Italy).
639 *Estuarine, Coastal and Shelf Science* 201. Vectors of Change in the Marine Environment: 123–131.
- 640 Como, Serena, and P. Magni. 2009. Temporal changes of a macrobenthic assemblage in harsh lagoon sediments.
641 *Estuarine, Coastal and Shelf Science* 83. Academic Press: 638–646.
- 642 Côté, I. M., E. S. Darling, and C. J. Brown. 2016. Interactions among ecosystem stressors and their importance in
643 conservation. *Proceedings of the Royal Society B: Biological Sciences* 283.

- 644 Cramer, W., J. Guiot, M. Fader, J. Garrabou, J.-P. Gattuso, A. Iglesias, M. A. A. Lange, et al. 2018. Climate change
645 and interconnected risks to sustainable development in the Mediterranean. *Nature Climate Change* 8.
- 646 Dedieu, K., C. Rabouille, G. Thouzeau, F. Jean, L. Chauvaud, J. Clavier, V. Mesnage, and S. Ogier. 2007a. Benthic
647 O₂ distribution and dynamics in a Mediterranean lagoon (Thau, France): An *in situ* microelectrode study.
648 *Estuarine, Coastal and Shelf Science* 72: 393–405.
- 649 Dedieu, K., Rabouille, C., Gilbert, F., Soetaert, K., Metzger, E., Simonucci, C., Jezequel, D., Prevot, F., Anschutz,
650 P., Hulth, S., Ogier, S., Mesnage, V., 2007b. Coupling of carbon, nitrogen and oxygen cycles in sediments
651 from a Mediterranean lagoon: a seasonal perspective. *Mar Ecol Prog Ser* 346, 45–59.
652 <https://doi.org/10.3354/meps07031>
- 653 Derolez, V., A. Fiandrino, D. Munaron, and M. Cadoret. 2014. Bilan sur les principales pressions pesant sur les
654 lagunes méditerranéennes et leurs liens avec l'état DCE. Rapport IFREMER.
- 655 Derolez, V., N. Malet, A. Fiandrino, F. Lagarde, M. Richard, V. Ouisse, B. Bec, and C. Aliaume. 2020. Fifty years
656 of ecological changes: Regime shifts and drivers in a coastal Mediterranean lagoon during oligotrophication.
657 *Science of the Total Environment* 732. Elsevier B.V: 183135.
- 658 Dethier, M. N., and S. D. Hacker. 2004. Improving management practices for invasive cordgrass in the Pacific
659 Northwest: A case study of *Spartina anglica*. *Washington Sea Grant Publication*.
- 660 de Wit, R., Stal, L.J., Lomstein, B.A., Herbert, R.A., van Gemerden, H., Viaroli, P., Cecherelli, V.U., Rodríguez-
661 Valera, F., Bartoli, M., Giordani, G., Azzoni, R., Schaub, B., Welsh, D.T., Donnelly, A., Cifuentes, A., Antón,
662 J., Finster, K., Nielsen, L.B., Pedersen, A.G.U., Neubauer, A.T., Colangelo, M.A., Heijs, S.K., 2001.
663 ROBUST: The ROLE of BUffering capacities in STabilising coastal lagoon ecosystems. *Cont Shelf Res* 21,
664 2021–2041. [https://doi.org/10.1016/S0278-4343\(01\)00040-1](https://doi.org/10.1016/S0278-4343(01)00040-1)
- 665 De Wit, R., A. Leruste, I. Le Fur, M. M. Sy, B. Bec, V. Ouisse, V. Derolez, and H. Rey-Valette. 2020. A
666 Multidisciplinary Approach for Restoration Ecology of Shallow Coastal Lagoons, a Case Study in South
667 France. *Frontiers in Ecology and Evolution* 8.
- 668 Dolbeth, M., Pardal, M.A., Lillebø, A.I., Azeiteiro, U., Marques, J.C., 2003. Short- and long-term effects of
669 eutrophication on the secondary production of an intertidal macrobenthic community. *Mar Biol* 143, 1229–
670 1238. <https://doi.org/10.1007/S00227-003-1133-5/TABLES/3>
- 671 Dupont, E., F. Gilbert, J. C. Poggiale, K. Dedieu, C. Rabouille, and G. Stora. 2007. Benthic macrofauna and
672 sediment reworking quantification in contrasted environments in the Thau Lagoon. *Estuarine, Coastal and*
673 *Shelf Science* 72: 522–533.
- 674 Durreau, A., L. Soissons, and V. Ouisse. 2021. Effet des épisodes extrêmes en milieu méditerranéen stressé. Phase
675 1: étude bibliographique et mise en place d'outils test *in situ*. 65p + Annexes. doi: [10.13155/80623](https://doi.org/10.13155/80623)
- 676 el Mahrad, B., Abalansa, S., Newton, A., Icely, J.D., Snoussi, M., Kacimi, I., 2020. Social-Environmental Analysis
677 for the Management of Coastal Lagoons in North Africa. *Front Environ Sci* 8, 37.
678 <https://doi.org/10.3389/FENVS.2020.00037/BIBTEX>
- 679 Espel, D., N. J. Diepens, O. Boutron, E. Buffan-Dubau, Y. Chérain, E. Coulet, P. Grillas, A. Probst, J. Silvestre,
680 and A. Elger. 2019. Dynamics of the seagrass *Zostera noltei* in a shallow Mediterranean lagoon exposed to
681 chemical contamination and other stressors. *Estuarine, Coastal and Shelf Science* 222: 1–12.
- 682 European Union, 2018. Commission Decision of February 12th 2018, in the Official Journal of the European
683 Union <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018D0229&from=HU>
- 684 Fastelli, P., and M. Renzi. 2019. Exposure of key marine species to sunscreens: Changing ecotoxicity as a possible
685 indirect effect of global warming. *Marine Pollution Bulletin* 149. Pergamon: 110517.
- 686 Ferreira, J.G., Vale, C., Soares, C.V., Salas, F., Stacey, P.E., Bricker, S.B., Silva, M.C., Marques, J.C., 2007.
687 Monitoring of coastal and transitional waters under the E.U. Water Framework Directive. *Environ Monit*
688 *Assess* 135, 195–216. <https://doi.org/10.1007/s10661-007-9643-0>
- 689 Foster, W. J., E. Arminot du Châtelet, and M. Rogerson. 2012. Testing benthic foraminiferal distributions as a
690 contemporary quantitative approach to biomonitoring estuarine heavy metal pollution. *Marine Pollution*
691 *Bulletin* 64: 1039–1048.
- 692 Franzo, A., R. Auriemma, F. Nasi, J. Vojvoda, A. Pallavicini, T. Cibic, and P. Del Negro. 2016. Benthic ecosystem
693 functioning in the severely contaminated Mar Piccolo of Taranto (Ionian Sea, Italy): focus on heterotrophic
694 pathways. *Environmental Science and Pollution Research* 23. Springer Verlag: 12645–12661.
- 695 Le Fur, I. 2018. Rôle des macrophytes dans la restauration des milieux lagunaires : successions écologiques. Thèse
696 de doctorat. Université de Montpellier.
- 697 Le Fur, I., de Wit, R., Plus, M., Oheix, J., Simier, M., Ouisse, V., 2018. Submerged benthic macrophytes in
698 Mediterranean lagoons: distribution patterns in relation to water chemistry and depth. *Hydrobiologia* 808, 175–
699 200. <https://doi.org/10.1007/S10750-017-3421-Y/FIGURES/7>
- 700 Le Fur, I., R. de Wit, M. Plus, J. Oheix, V. Derolez, M. Simier, N. Malet, and V. Ouisse. 2019. Re-oligotrophication
701 trajectories of macrophyte assemblages in Mediterranean coastal lagoons studied from 17-years' time-series.
702 *Marine Ecology Progress Series* 608: 13–32.

- 703 Gagic, V., I. Bartomeus, T. Jonsson, A. Taylor, C. Winqvist, C. Fischer, E. M. Slade, et al. 2015. Functional
 704 identity and diversity of animals predict ecosystem functioning better than species-based indices. *Proceedings*
 705 *of the Royal Society B: Biological Sciences* 282: 20142620.
- 706 Galgani, F., J. Senia, J. L. Guillou, T. Laugier, D. Munaron, B. Andral, B. Guillaume, et al. 2009. Assessment of
 707 the environmental quality of french continental mediterranean lagoons with oyster embryo bioassay. *Archives*
 708 *of Environmental Contamination and Toxicology* 57: 540–551.
- 709 Gallardi, D. 2014. Effects of Bivalve Aquaculture on the Environment and Their Possible Mitigation : A Review.
 710 *Fisheries and Aquaculture Journal* 5: 8.
- 711 García-Sánchez, M., I. M. Pérez-Ruzafa, C. Marcos, and A. Pérez-Ruzafa. 2012. Suitability of benthic macrophyte
 712 indices (EEI, E-MaQI and BENTHOS) for detecting anthropogenic pressures in a Mediterranean coastal
 713 lagoon (Mar Menor, Spain). *Ecological Indicators* 19: 48–60.
- 714 Ghezzi, M., M. Pellizzato, F. De Pascalis, S. Silvestri, and G. Umgiesser. 2018. Natural resources and climate
 715 change: A study of the potential impact on Manila clam in the Venice lagoon. *Science of the Total Environment*
 716 645. Elsevier B.V.: 419–430.
- 717 Gissi, E., E. Manea, A. D. Mazaris, S. Fraschetti, V. Almpandou, S. Bevilacqua, M. Coll, et al. 2021. A review
 718 of the combined effects of climate change and other local human stressors on the marine environment. *Science*
 719 *of the Total Environment*. Elsevier.
- 720 Green, D. S., B. Boots, J. Sigwart, S. Jiang, and C. Rocha. 2016. Effects of conventional and biodegradable
 721 microplastics on a marine ecosystem engineer (*Arenicola marina*) and sediment nutrient cycling.
 722 *Environmental Pollution* 208. Elsevier: 426–434.
- 723 Halpern, B. S., Frazier, M., Potapenko, J., Casey, K. S., Koenig, K., Longo, C., ... & Walbridge, S. 2015. Spatial
 724 and temporal changes in cumulative human impacts on the world’s ocean. *Nature communications*, 6(1), 1-7.
- 725 Harzallah, A., and A. Chapelle. 2002. Contribution of climate variability to occurrences of anoxic crises
 726 “malaïgues” in the Thau lagoon (southern France). *Oceanologica Acta* 25: 79–86.
- 727 Ieno, E. N., Solan, M., Batty, P., & Pierce, G. J. 2006. How biodiversity affects ecosystem functioning: roles of
 728 infaunal species richness, identity and density in the marine benthos. *Marine Ecology Progress Series*, 311,
 729 263-271
- 730 IPBES (2019): Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-
 731 Policy Platform on Biodiversity and Ecosystem Services. E. S. Brondizio, J. Settele, S. Díaz, and H. T. Ngo
 732 (editors). IPBES secretariat, Bonn, Germany. 1148 pages. <https://doi.org/10.5281/zenodo.3831673>
- 733 Isbell, F., A. Gonzalez, M. Loreau, J. Cowles, S. Díaz, A. Hector, G. M. MacE, et al. 2017. Linking the influence
 734 and dependence of people on biodiversity across scales. *Nature* 546: 65–72.
- 735 de Jonge, V. N., and M. Elliott. 2001. Eutrophication. *Encyclopedia of Ocean Sciences* 2: 852–870.
- 736 Jones, A., Schaal, G., Boyé, A., Creemers, M., Derolez, V., Desroy, N., Fiandrino, A., Mouton, T.L., Simier, M.,
 737 Smith, N., Ouisse, V., 2022. PREPRINT. Disentangling the effects of eutrophication and natural variability on
 738 macrobenthic communities across French coastal lagoons. <https://doi.org/10.1101/2022.08.18.504439>
- 739 El Kateb, A., C. Stalder, C. Neururer, R. Fentimen, J. E. Spangenberg, and S. Spezzaferri. 2018. Distribution of
 740 benthic foraminiferal assemblages in the transitional environment of the Djerba lagoon (Tunisia). *Swiss*
 741 *Journal of Geosciences* 111. Birkhauser Verlag AG: 561–578.
- 742 Khedhri, I., A. Afli, and L. Aleya. 2017. Structuring factors of the spatio-temporal variability of macrozoobenthos
 743 assemblages in a southern Mediterranean lagoon: How useful for bioindication is a multi-biotic indices
 744 approach? *Marine Pollution Bulletin* 114: 515–527.
- 745 Khedhri, I., H. Djabou, and A. Afli. 2015. Trophic and functional organization of the benthic macrofauna in the
 746 lagoon of Boughrara - Tunisia (SW Mediterranean Sea). *Journal of the Marine Biological Association of the*
 747 *United Kingdom* 95: 647–659.
- 748 Khedhri, I., H. Djabou, and A. Afli. 2016. Does increased connectivity with the Mediterranean Sea improve the
 749 ecological status of the macroinvertebrates in the lagoon of Boughrara (SW Mediterranean)? *Community*
 750 *Ecology* 17: 156–166.
- 751 Korpinen, S., L. Laamanen, L. Bergström, M. Nurmi, J. H. Andersen, J. Haapaniemi, E. T. Harvey, et al. 2021.
 752 Combined effects of human pressures on Europe’s marine ecosystems. *Ambio* 50: 1325–1336.
- 753 Kristensen, P., Whalley, C., Zal, F.N.N., Christiansen, T., 2018. European waters Assessment of status and
 754 pressures 2018. EEA Report No 7/2018
- 755 Kysely, J., S. Beguería, R. Beranová, L. Gaál, and J. I. López-Moreno. 2012. Different patterns of climate change
 756 scenarios for short-term and multi-day precipitation extremes in the Mediterranean. *Global and Planetary*
 757 *Change* 98–99: 63–72.
- 758 Lacoste, É., B. Bec, P. Le Gall, F. Boufahja, P. Raimbault, G. Messiaen, V. Ouisse, et al. 2022. Benthic-pelagic
 759 coupling under juvenile oyster influence in a French Mediterranean coastal lagoon (Thau Lagoon). *Estuarine,*
 760 *Coastal and Shelf Science* 267.

- 761 Lacoste, É., F. Boufahja, C. Pelaprat, P. Le Gall, T. Berteaux, G. Messiaen, S. Mortreux, et al. 2020. First
762 simultaneous assessment of macro- and meiobenthic community response to juvenile shellfish culture in a
763 Mediterranean coastal lagoon (Thau, France). *Ecological Indicators* 115.
- 764 Lacoste, É., and N. Gaertner-Mazouni. 2015. Biofouling impact on production and ecosystem functioning: A
765 review for bivalve aquaculture. *Reviews in Aquaculture* 7: 187–196.
- 766 Lacoste, É., C. W. McKindsey, P. Archambault. 2020. Biodiversity–Ecosystem Functioning (BEF) approach to
767 further understanding aquaculture–environment interactions with application to bivalve culture and benthic
768 ecosystems. *Reviews in Aquaculture* 12:4, 2027–2041. Doi: 10.1111/raq.12420
- 769 Lam-Gordillo, O., R. Baring, and S. Dittmann. 2020. Ecosystem functioning and functional approaches on marine
770 macrobenthic fauna: A research synthesis towards a global consensus. *Ecological Indicators*. Elsevier.
- 771 Leenhardt, S., Mamy, L., Pesce, S., Sanchez, W., ..., Tournebize, J., 2022. Impacts des produits
772 phytopharmaceutiques sur la biodiversité et les services écosystémiques. Synthèse du rapport d’ESCo, INRAE
773 - Ifremer (France).
- 774 León, V. M., R. Moreno-González, V. García, and J. A. Campillo. 2017. Impact of flash flood events on the
775 distribution of organic pollutants in surface sediments from a Mediterranean coastal lagoon (Mar Menor, SE
776 Spain). *Environmental Science and Pollution Research* 24. Springer Verlag: 4284–4300.
- 777 Lloret, J., A. Marín, and L. Marín-Guirao. 2008. Is coastal lagoon eutrophication likely to be aggravated by global
778 climate change? *Estuarine, Coastal and Shelf Science* 78: 403–412.
- 779 Magri, M., Benelli, S., Bonaglia, S., Zilius, M., Castaldelli, G., Bartoli, M., 2020. The effects of hydrological
780 extremes on denitrification, dissimilatory nitrate reduction to ammonium (DNRA) and mineralization in a
781 coastal lagoon. *Science of The Total Environment* 740, 140169.
782 <https://doi.org/10.1016/j.scitotenv.2020.140169>
- 783 Mahé, M., D. Delanghe, R. Grisel, J. Poggiale, M. 2021. Distribution of Manila clam, *Ruditapes philippinarum*,
784 into Berre Lagoon according to the environmental condition. *Vie et milieu*.
- 785 Mahmoudi, E., A. Hedfi, N. Essid, H. Beyrem, P. Aïssa, F. Boufahja, and P. Vitiello. 2008. Mussel-farming effects
786 on Mediterranean benthic nematode communities. *Nematology* 10: 323–333
- 787 Mancinelli, G., L. Carrozzo, M. L. Costantini, L. Rossi, G. Marini, and M. Pinna. 2013. Occurrence of the Atlantic
788 blue crab *Callinectes sapidus* Rathbun, 1896 in two Mediterranean coastal habitats: Temporary visitor or
789 permanent resident? *Estuarine Coastal and Shelf Science* 135: 46–56.
- 790 Mancinelli, G., P. Chainho, L. Cilenti, S. Falco, K. Kaporis, G. Katselis, and F. Ribeiro. 2017. The Atlantic blue
791 crab *Callinectes sapidus* in southern European coastal waters: Distribution, impact and prospective invasion
792 management strategies. *Marine Pollution Bulletin* 119: 5–11.
- 793 Maneas, G., E. Makopoulou, D. Bousbouras, H. Berg, and S. Manzoni. 2019. Anthropogenic changes in a
794 Mediterranean Coastal Wetland during the last century—The case of Gialova Lagoon, Messinia, Greece.
795 *Waters* 11: 350.
- 796 Mantovani, S., G. Castaldelli, R. Rossi, and E. A. Fano. 2006. The infaunal community in experimentally seeded
797 low and high density Manila clam (*Tapes philippinarum*) beds in a Po River Delta lagoon (Italy). *Ices Journal*
798 *of Marine Science* 63: 860–866.
- 799 Marchessaux, G., B. Belloni, J. Gadreaud, and D. Thibault. 2021a. Predation assessment of the invasive ctenophore
800 *Mnemiopsis leidyi* in a French Mediterranean lagoon. *Journal of Plankton Research* 43: 161–179.
- 801 Marchessaux, G., M. Harmelin-Vivien, M. Ourgaud, D. Bănaru, L. Guilloux, B. Belloni, B. Lebreton, G. Guillou,
802 and D. Thibault. 2021b. First overview on trophic relationships of the invasive ctenophore *Mnemiopsis leidyi*
803 in a Mediterranean coastal lagoon (Berre Lagoon, France): benthic–pelagic coupling evidenced by carbon and
804 nitrogen stable isotope composition. *Regional Studies in Marine Science* 41: 101570.
- 805 De Marchi, L., L. R. Vieira, L. Intorre, V. Meucci, F. Battaglia, C. Pretti, A. M. V. M. Soares, and R. Freitas.
806 2022. Will extreme weather events influence the toxic impacts of caffeine in coastal systems? Comparison
807 between two widely used bioindicator species. *Chemosphere* 297. Pergamon: 134069.
- 808 Marchini, A., J. Ferrario, A. Sfriso, and A. Occhipinti-Ambrogi. 2015. Current status and trends of biological
809 invasions in the Lagoon of Venice, a hotspot of marine NIS introductions in the Mediterranean Sea. *Biological*
810 *Invasions* 17: 2943–2962.
- 811 Marín-Guirao, L., A. Cesar, A. Marín, and R. Vita. 2005. Assessment of sediment metal contamination in the Mar
812 Menor coastal lagoon (SE Spain): Metal distribution, toxicity, bioaccumulation and benthic community
813 structure. *Ciencias Marinas* 31: 413–428.
- 814 Martin, S., G. Thouzeau, M. Richard, L. Chauvaud, F. Jean, and J. Clavier. 2007. Benthic community respiration
815 in areas impacted by the invasive mollusk *Crepidula fornicata*. *Marine Ecology Progress Series* 347: 51–60.
- 816 Martins, M. V. A., Helali, M.A., Zaaboub, N., I. Boukef-BenOmrane, F. Frontalini, D. Reis, H. Portela, et al. 2016.
817 Organic matter quantity and quality, metals availability and foraminiferal assemblages as environmental proxy
818 applied to the Bizerte Lagoon (Tunisia). *Marine Pollution Bulletin* 105: 161–179.
- 819 Mason, N. W. H., D. Mouillot, W. G. Lee, and J. B. Wilson. 2005. Functional richness, functional evenness and
820 functional divergence: The primary components of functional diversity. *Oikos* 111: 112–118.

- 821 Mazor, T., C. Doropoulos, F. Schwarzmüller, D. W. Gladish, N. Kumaran, K. Merkel, M. Di Marco, and V.
822 Gagic. 2018. Global mismatch of policy and research on drivers of biodiversity loss. *Nature Ecology and*
823 *Evolution* 2. Springer US: 1071–1074.
- 824 Millennium Ecosystem Assessment, 2005. Ecosystems and human well-being: synthesis. Island Press,
825 Washington, DC.
- 826 Mercurio, M., C. Pierri, F. Cardone, and G. Corriero. 2021. Temporal and spatial variations of *Geodia cydonium*
827 (Jameson) (porifera, demospongiae) in the mediterranean confined environments. *Diversity* 13.
- 828 Metzger, E., C. Simonucci, E. Viollier, G. Sarazin, F. Prevot, and D. Jezequel. 2007. Benthic response to shellfish
829 farming in Thau lagoon: Pore water signature. *Estuarine Coastal and Shelf Science* 72: 406–419.
- 830 Meyer, S. T., C. Koch, and W. W. Weisser. 2015. Towards a standardized Rapid Ecosystem Function Assessment
831 (REFA). *Trends in Ecology and Evolution* 30. Elsevier Ltd: 390–397.
- 832 Micheli, F., B. S. Halpern, S. Walbridge, S. Ciriaco, F. Ferretti, S. Fraschetti, R. Lewison, L. Nykjaer, and A. A.
833 Rosenberg. 2013. Cumulative human impacts on Mediterranean and Black Sea marine ecosystems: Assessing
834 current pressures and opportunities. *PLoS ONE* 8.
- 835 Miller, D. C., C. L. Muir, and O. A. Hauser. 2002. Detrimental effects of sedimentation on marine benthos: What
836 can be learned from natural processes and rates? *Ecological Engineering* 19: 211–232.
- 837 Mistri, M. 2003. The non-indigenous mussel *Musculista senhousia* in an Adriatic lagoon: effects on benthic
838 community over a ten year period. *Journal of the Marine Biological Association of the United Kingdom* 83:
839 1277–1278.
- 840 Mistri, M., and C. Munari. 2012. Clam farming generates CO₂: A study case in the Marinetta lagoon (Italy).
841 *Marine Pollution Bulletin* 64: 2261–2264.
- 842 Morant, D., Perennou, C., Camacho, A., 2021. Assessment of the Pressure Level over Lentic Waterbodies through
843 the Estimation of Land Uses in the Catchment and Hydro-Morphological Alterations: The LUPLES Method.
844 *Applied Sciences* 11, 1633. <https://doi.org/10.3390/app11041633>
- 845 Moreno-González, R., and V. M. León. 2017. Presence and distribution of current-use pesticides in surface marine
846 sediments from a Mediterranean coastal lagoon (SE Spain). *Environmental Science and Pollution Research*
847 24. Springer Verlag: 8033–8048.
- 848 Moreno, M., F. Semprucci, L. Vezzulli, M. Balsamo, M. Fabiano, and G. Albertelli. 2011. The use of nematodes
849 in assessing ecological quality status in the Mediterranean coastal ecosystems. *Ecological Indicators* 11.
850 Elsevier: 328–336.
- 851 Moschino, V., L. Chicharo, and M. G. Marin. 2011. Long-term effects of fishing on physiological performance of
852 the Manila clam (*Ruditapes philippinarum*) in the Lagoon of Venice. *Scientia Marina* 75: 103–110..
- 853 Munari, C., and M. Mistri. 2008. The performance of benthic indicators of ecological change in Adriatic coastal
854 lagoons: Throwing the baby with the water? *Marine Pollution Bulletin* 56. Pergamon: 95–105.
- 855 Munari, C., and M. Mistri. 2014. Spatio-temporal pattern of community development in dredged material used for
856 habitat enhancement: A study case in a brackish lagoon. *Marine pollution bulletin* 89. Elsevier Ltd: 340–7.
- 857 Munari, Cristina. 2008. Effects of the exotic invader *Musculista senhousia* on benthic communities of two
858 Mediterranean lagoons. *Hydrobiologia* 611: 29–43.
- 859 Munari, Cristina. 2011. Effects of the 2003 European heatwave on the benthic community of a severe transitional
860 ecosystem (Comacchio Saltworks, Italy). *Marine Pollution Bulletin* 62. Pergamon: 2761–2770.
- 861 Murphy, A.E., Nizzoli, D., Bartoli, M., Smyth, A.R., Castaldelli, G., Anderson, I.C., 2018. Variation in benthic
862 metabolism and nitrogen cycling across clam aquaculture sites. *Mar Pollut Bull* 127, 524–535.
863 <https://doi.org/10.1016/j.marpolbul.2017.12.003>
- 864 Nasi, F., M. C. Nordström, E. Bonsdorff, R. Auriemma, T. Cibic, and P. Del Negro. 2018. Functional biodiversity
865 of marine soft-sediment polychaetes from two Mediterranean coastal areas in relation to environmental stress.
866 *Marine Environmental Research* 137: 121–132.
- 867 Nebot-Colomer, E., Álvarez, E., Belando, M.D., Deudero, S., Catanese, G., Bernardeau-Esteller, J., García-
868 Muñoz, R., Ramos-Segura, A., Ruiz, J.M., Vázquez-Luis, M., 2022. Living under threat: Will one of the last
869 *Pinna nobilis* populations be able to survive? *Aquat Conserv* 32, 1–13. <https://doi.org/10.1002/aqc.3738>
- 870 Newton, A., A. C. Brito, J. D. Icely, V. Derolez, I. Clara, S. Angus, G. Schernewski, et al. 2018. Assessing,
871 quantifying and valuing the ecosystem services of coastal lagoons. *Journal for Nature Conservation* 44.
872 Elsevier GmbH.: 50–65.
- 873 Newton, A., J. Icely, S. Cristina, A. Brito, A. C. Cardoso, F. Colijn, S. D. Riva, et al. 2014. An overview of
874 ecological status, vulnerability and future perspectives of European large shallow, semi-enclosed coastal
875 systems, lagoons and transitional waters. *Estuarine, Coastal and Shelf Science* 140. Academic Press: 95–122.
- 876 Nizzoli, D, M. Bartoli, and P. Viaroli. 2006a. Nitrogen and phosphorus budgets during a farming cycle of the
877 Manila clam *Ruditapes philippinarum*: An in situ experiment. *Aquaculture* 261: 98–108.
- 878 Nizzoli, D, M. Bartoli, and P. Viaroli. 2007. Oxygen and ammonium dynamics during a farming cycle of the
879 bivalve *Tapes philippinarum*. *Hydrobiologia* 587: 25–36.

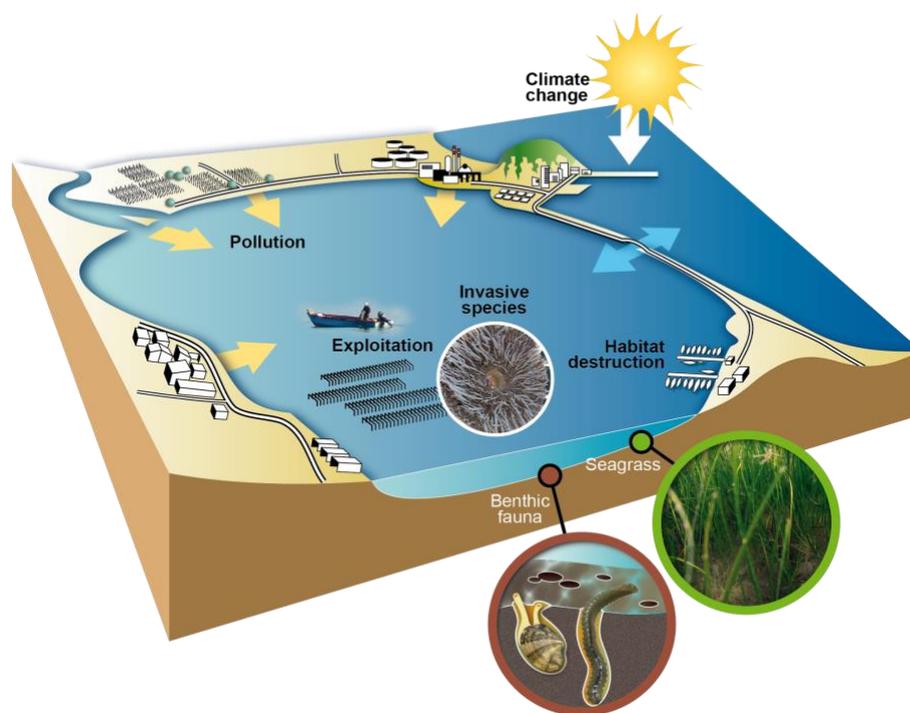
- 880 Nizzoli, Daniele, D. T. Welsh, M. Bartoli, and P. Viaroli. 2005. Impacts of mussel (*Mytilus galloprovincialis*)
881 farming on oxygen consumption and nutrient recycling in a eutrophic coastal lagoon. In *Hydrobiologia*,
882 550:183–198.
- 883 Nizzoli, Daniele, D. T. Welsh, E. A. Fano, and P. Viaroli. 2006b. Impact of clam and mussel farming on benthic
884 metabolism and nitrogen cycling, with emphasis on nitrate reduction pathways. *Marine Ecology Progress*
885 *Series* 315: 151–165.
- 886 Nizzoli, Daniele, D. Welsh, and P. Viaroli. 2011. Seasonal nitrogen and phosphorus dynamics during benthic clam
887 and suspended mussel cultivation. *Marine pollution bulletin* 62. Elsevier Ltd: 1276–87.
- 888 Nonnis Marzano, C., L. Scalera Liaci, A. Fianchini, F. Gravina, M. Mercurio, and G. Corriero. 2003. Distribution,
889 persistence and change in the macrobenthos of the lagoon of Lesina (Apulia, southern Adriatic Sea).
890 *Oceanologica Acta* 26: 57–66.
- 891 von der Ohe, P. C., V. Dulio, J. Slobodnik, E. De Deckere, R. Kühne, R. U. Ebert, A. Ginebreda, W. De Cooman,
892 G. Schüürmann, and W. Brack. 2011. A new risk assessment approach for the prioritization of 500 classical
893 and emerging organic microcontaminants as potential river basin specific pollutants under the European Water
894 Framework Directive. *Science of the Total Environment* 409. Elsevier: 2064–2077.
- 895 Orabi, O. H., A. A. El-Badry, and A. M. Badr-ElDin. 2017. Benthic foraminifera for heavy metal pollution
896 monitoring: A case study from Burullus Lagoon of Egypt. *Marine Pollution Bulletin* 121: 411–417.
- 897 Orfanidis, S., Dencheva, K., Nakou, K., Tsioli, S., Papanthanasidou, V., Rosati, I., 2014. Benthic macrophyte metrics
898 as bioindicators of water quality: towards overcoming typological boundaries and methodological tradition in
899 Mediterranean and Black Seas. *Hydrobiologia*. <https://doi.org/10.1007/s10750-014-1938-x>
- 900 Ouisse, V., A. Fiandrino, R. De Wit, and A. Giraud. 2014. *DEvenir du Phosphore et de l'Azote dans un contexte*
901 *de Restauration des milieux lagunaires méditerranéens - DEPART* –. Vol. 3211998.
- 902 Ouisse, V., A. Fiandrino, R. de Wit, and N. Malet. 2013. *Restauration des écosystèmes lagunaires : évaluation du*
903 *rôle du sédiment et des herbiers à phanérogames Rapport final du Contrat n° 2012 1835*.
- 904 Pasqualini, V., V. Derolez, M. Garrido, V. Orsoni, Y. Baldi, S. Etourneau, V. Leoni, et al. 2017. Spatiotemporal
905 dynamics of submerged macrophyte status and watershed exploitation in a Mediterranean coastal lagoon:
906 Understanding critical factors in ecosystem degradation and restoration. *Ecological Engineering* 102. Elsevier
907 B.V.: 1–14.
- 908 Pearson, T.H., Rosenberg, R., 1978. Macrobenthic succession in relation to organic enrichment and pollution of
909 the marine environment. *Oceanography and marine biology annual review* 16, 229–311.
910 <https://doi.org/10.1111/j.1540-5834.2012.00707.x>
- 911 Pérez-Ruzafa, Angel, I. M. Pérez-Ruzafa, A. Newton, and C. Marcos. 2019. Coastal Lagoons: Environmental
912 Variability, Ecosystem Complexity, and Goods and Services Uniformity. In *Coasts and Estuaries*, ed. E.
913 Wolanski, J. W. Day, M. Elliott, and R. Ramachandran, 253–276. Elsevier.
- 914 Pitacco, V., M. Mistri, C. R. Ferrari, A. Sfriso, A. A. Sfriso, and C. Munari. 2020. Multiannual trend of micro-
915 pollutants in sediments and benthic community response in a mediterranean lagoon (Sacca di Goro, Italy).
916 *Water (Switzerland)* 12.
- 917 Pitacco, V., M. Mistri, and C. Munari. 2018. Long-term variability of macrobenthic community in a shallow
918 coastal lagoon (Valli di Comacchio, northern Adriatic): Is community resistant to climate changes? *Marine*
919 *Environmental Research* 137. Elsevier: 73–87.
- 920 Poikane, S., F. Salas Herrero, M. G. Kelly, A. Borja, S. Birk, and W. van de Bund. 2020. European aquatic
921 ecological assessment methods: A critical review of their sensitivity to key pressures. *Science of the Total*
922 *Environment* 740. The Authors: 140075.
- 923 Ponti, M., A. Pasteris, R. Guerra, and M. Abbiati. 2009. Impacts of maintenance channel dredging in a northern
924 Adriatic coastal lagoon. II: Effects on macrobenthic assemblages in channels and ponds. *Estuarine, Coastal*
925 *and Shelf Science* 85: 143–150.
- 926 Pranovi, F., Giovanardi, O., & Franceschini, G. 1998. Recolonization dynamics in areas disturbed by bottom
927 fishing gears. *Hydrobiologia*, 375–76, 125–135. <https://doi.org/10.1023/a:1017056905625>
- 928 Pranovi, F., da Ponte, F., Raicevich, S., Giovanardi, O. 2004. A multidisciplinary study of the immediate effects
929 of mechanical clam harvesting in the Venice Lagoon. *ICES Journal of Marine Science*, 61(1), 43–52.
930 <https://doi.org/10.1016/j.jcesjms.2003.10.003>
- 931 Pranovi, F., G. Franceschini, M. Casale, M. Zucchetta, P. Torricelli, and O. Giovanardi. 2006. An Ecological
932 Imbalance Induced by a Non-Native Species: The Manila Clam in the Venice Lagoon. *Biological Invasions* 8:
933 595–609.
- 934 Quevauviller, P. 2011. Adapting to climate change: Reducing water-related risks in Europe - EU policy and
935 research considerations. *Environmental Science and Policy* 14. Elsevier: 722–729.
- 936 Quigley, M. P., and J. A. Hall. 1999. Recovery of macrobenthic communities after maintenance dredging in the
937 Blyth estuary, north-east England. *Aquatic Conservation: Marine and Freshwater Ecosystems* 9: 63–73.

- 938 Ragueneau, O., L. Chauvaud, B. Moriceau, A. Leynaert, G. Thouzeau, A. Donval, F. Le Loc'h, and F. Jean. 2005.
 939 Biodeposition by an invasive suspension feeder impacts the biogeochemical cycle of Si in a coastal ecosystem
 940 (Bay of Brest, France). *Biogeochemistry* 75. Springer: 19–41.
- 941 Renzi, M., V. H. Pauna, F. Provenza, C. Munari, and M. Mistri. 2020. Marine litter in transitional water
 942 ecosystems: State of the art review based on a bibliometric analysis. *Water (Switzerland)* 12.
- 943 Reyjol, Y., C. Argillier, W. Bonne, A. Borja, A. D. Buijse, A. C. Cardoso, M. Daufresne, et al. 2014. Assessing
 944 the ecological status in the context of the European Water Framework Directive: Where do we go now? *Science*
 945 *of the Total Environment* 497–498. Elsevier B.V.: 332–344.
- 946 Rigaud, S., J. M. Garnier, X. Moreau, L. De Jong-Moreau, N. Mayot, P. Chaurand, and O. Radakovitch. 2019.
 947 How to assess trace elements bioavailability for benthic organisms in lowly to moderately contaminated coastal
 948 sediments? *Marine Pollution Bulletin* 140: 86–100.
- 949 Rigaud, S., Deflandre, B., Grenz, C., Cesbron, F., Pozzato, L., Voltz, B., Grémare, A., Romero-Ramirez, A.,
 950 Mirleau, P., Meulé, S., Faure, V., Mayot, N., Michotey, V., Bonin, P., Pascal, L., Cordier, M.-A., Lamarque,
 951 B., Tenório, M., Radakovitch, O., 2021. Benthic oxygen dynamics and implication for the maintenance of
 952 chronic hypoxia and ecosystem degradation in the Berre lagoon (France). *Estuar Coast Shelf Sci* 258, 107437.
 953 <https://doi.org/10.1016/j.ecss.2021.107437>
- 954 Rigaud, S., Giorgio, C. di, Radakovitch, O., Garnier, J.M., Méo, M. de, 2012. Genotoxicity of sediment extracts
 955 of the Berre lagoon (France). *Chemosphere* 88, 937–944. <https://doi.org/10.1016/j.chemosphere.2012.03.023>
- 956 Rhoads, D., McCall, P., Yingst, J., 1978. Disturbance and Production on the Estuarine Seafloor: Dredge-spoil
 957 disposal in estuaries such as Long Island Sound can be managed in ways that enhance. *Am Sci* 66, 577586.
- 958 Ruiz, F., M. L. González-Regalado, E. Galán, M. I. González, M. I. Prudencio, M. I. Dias, M. Abad, A. Toscano,
 959 J. Prenda, and E. X. M. García. 2012. Benthic foraminifera as bioindicators of anthropogenic impacts in two
 960 North African Lagoons: A comparison with ostracod assemblages. *Revista Mexicana de Ciencias Geológicas*
 961 29: 527–533.
- 962 Rysgaard, S., Risgaard-Petersen, N., Sloth, N.P., 1996. Nitrification, denitrification, and nitrate ammonification
 963 in sediments of two coastal lagoons in Southern France. *Hydrobiologia* 329, 133–141.
 964 <https://doi.org/10.1007/BF00034553>
- 965 Said, O. Ben, M. Goñi-Urriza, M. El Bour, P. Aissa, and R. Duran. 2010. Bacterial community structure of
 966 sediments of the bizerte lagoon (Tunisia), a southern mediterranean coastal anthropized lagoon. *Microbial*
 967 *Ecology* 59: 445–456.
- 968 Saidi, I., O. Ben Said, J. Ben Abdelmalek, S. Jouili, L. Chicharo, and H. Beyrem. 2019. Impact of heavy metals
 969 of industrial plant wastewater on benthic communities of Bizerte Lagoon (Tunisia). *Chemistry and Ecology*
 970 35: 746–774.
- 971 Ben Salem, F., O. Ben Said, C. Cravo-Laureau, E. Mahmoudi, N. Bru, M. Monperrus, and R. Duran. 2019.
 972 Bacterial community assemblages in sediments under high anthropogenic pressure at Ichkeul Lake/Bizerte
 973 Lagoon hydrological system, Tunisia. *Environmental Pollution* 252: 644–656.
- 974 Schmidt, S., J. L. Gonzalez, P. Lecroart, J. Tronczynski, I. Billy, and J. M. Jouanneau. 2007. Bioturbation at the
 975 water-sediment interface of the Thau Lagoon: impact of shellfish farming. *Aquatic Living Resources* 20: 163–
 976 169.
- 977 Schramm, W., 1999. Factors influencing seaweed responses to eutrophication : some results from EU-project
 978 EUMAC. *J Appl Phycol* 11, 69–78.
- 979 Semprucci, F., V. Losi, and M. Moreno. 2015. A review of Italian research on free-living marine nematodes and
 980 the future perspectives on their use as Ecological Indicators (EcoInds). *Mediterranean Marine Science*.
 981 Hellenic Centre for Marine Research.
- 982 Sfriso, A, F. Chiara, and M. Antonio. 2005. Sedimentation rates and erosion processes in the lagoon of Venice.
 983 *Environment International* 31. Lagoon of Venice: Loads, Distribution, and Effects of Nutrients and Pollutants:
 984 983–992.
- 985 Sfriso, A, C. Facca, and P. Ghetti. 2003. Temporal and spatial changes of macroalgae and phytoplankton in a
 986 Mediterranean coastal area: the Venice lagoon as a case study. *Marine Environmental Research* 56: 617–636.
- 987 Sfriso, A., Facca, C., Ghetti, P.F., 2009. Validation of the Macrophyte Quality Index (MaQI) set up to assess the
 988 ecological status of Italian marine transitional environments. *Hydrobiologia* 617, 117–141.
 989 <https://doi.org/10.1007/s10750-008-9540-8>
- 990 Sfriso, A, M. A. Wolf, S. Maistro, K. Sciuto, and I. Moro. 2012. Spreading and autoecology of the invasive species
 991 *Gracilaria vermiculophylla* (Gracilariales, Rhodophyta) in the lagoons of the north-western Adriatic Sea
 992 (Mediterranean Sea, Italy). *Estuarine, Coastal and Shelf Science* 114. Research and Management for the
 993 Conservation of Coastal Lagoon Ecosystems: 192–198.
- 994 Sfriso, Adriano, A. Buosi, M. A. Wolf, and A. A. Sfriso. 2020. Invasion of alien macroalgae in the venice lagoon,
 995 a pest or a resource? *Aquatic Invasions* 15: 245–270.

- 996 Simboura, N., and S. Reizopoulou. 2008. An intercalibration of classification metrics of benthic
997 macroinvertebrates in coastal and transitional ecosystems of the Eastern Mediterranean ecoregion (Greece).
998 *Marine Pollution Bulletin* 56: 116–126.
- 999 Solan, M., Cardinale, B. J., Downing, A. L., Engelhardt, K. A., Ruesink, J. L., & Srivastava, D. S. 2004. Extinction
1000 and ecosystem function in the marine benthos. *Science*, 306(5699), 1177-1180.
- 1001 Souchu, P., Gasc, A., Collos, Y., Vaquer, A., Tournier, H., Bibent, B., Deslous-Paoli, J., 1998. Biogeochemical
1002 aspects of bottom anoxia in a Mediterranean lagoon (Thau, France). *Mar Ecol Prog Ser* 164, 135–146.
1003 <https://doi.org/10.3354/meps164135>
- 1004 Stachowitsch, M. 1992. Benthic communities: Eutrophication's “memory mode”. In *Marine Coastal*
1005 *Eutrophication* (Ed., Vollenwieder, R.A., Marchetti, R., Viviani, R.). Elsevier, Amsterdam, London, New
1006 York, Tokyo. pp. 1017-1028.
- 1007 Streftaris, N., and A. Zenetos. 2006. Alien Marine Species in the Mediterranean - the 100 ‘Worst Invasives’ and
1008 their Impact. *Mediterranean Marine Science* 7: 87–118.
- 1009 Strong, J. A., E. Andonegi, K. C. K. Bizsel, R. Danovaro, M. Elliott, A. Franco, E. Garces, et al. 2015. Marine
1010 biodiversity and ecosystem function relationships: The potential for practical monitoring applications.
1011 *Estuarine, Coastal and Shelf Science* 161: 46–64.
- 1012 Telahigue, K., I. Rabeh, L. Chouba, Z. Mdaini, M. El Cafsi, L. Mhadhbi, and T. Hajji. 2022. Assessment of the
1013 heavy metal levels and biomarker responses in the smooth scallop *Flexopecten glaber* from a heavily urbanized
1014 Mediterranean lagoon (Bizerte lagoon). *Environmental Monitoring and Assessment* 194. Springer Science and
1015 Business Media Deutschland GmbH.
- 1016 Thouzeau, G., J. Grall, J. Clavier, L. Chauvaud, F. Jean, A. Leynaert, S. ni Longphuir, E. Amice, and D.
1017 Amouroux. 2007. Spatial and temporal variability of benthic biogeochemical fluxes associated with
1018 macrophytic and macrofaunal distributions in the Thau lagoon (France). *Estuarine, Coastal and Shelf Science*
1019 72: 432–446.
- 1020 Troussellier, M., Deslous-Paoli, J.M., 2001. La lagune de Thau: un site atelier pour l’acquisition, l’intégration et
1021 la valorisation des connaissances. *Oceanis* 27, 257–289.
- 1022 Tlig-Zouari, S., L. Rabaoui, A. Cosentino, I. Irathni, H. Ghrairi, and O. K. Ben Hassine. 2011. Macrofauna
1023 associated with an introduced oyster, *Pinctada radiata*: Spatial scale implications of community differences.
1024 *Journal of Sea Research* 65. Elsevier B.V.: 161–169.
- 1025 Underwood, A. J. 1994. On beyond BACI: Sampling designs that might reliably detect environmental
1026 disturbances. *Ecological Applications* 4. John Wiley & Sons, Ltd: 3–15.
- 1027 Viaroli, P, M. Bartoli, G. Giordani, R. Azzoni, and D. Nizzoli. 2003. Short term changes of benthic fluxes during
1028 clam harvesting in a coastal lagoon (Sacca di Goro, po river delta). *Chemistry and Ecology* 19: 189–206.
- 1029 Viaroli, P, M. Bartoli, G. Giordani, and M. Naldi. 2008. Community shifts, alternative stable states,
1030 biogeochemical controls and feedbacks in eutrophic coastal lagoons : a brief overview. *Aquatic Conservation:*
1031 *Marine and Freshwater Ecosystems* 18: 105–117.
- 1032 Vignes, F., E. Barbone, P. Breber, R. D’Adamo, R. Leonilde, N. Ungaro, S. Focardi, M. Renzi, and A. Basset.
1033 2009. Spatial and temporal description of the dystrophic crisis in Lesina lagoon during summer 2008.
1034 *Transitional Waters Bulletin* 3: 47–62.
- 1035 Zaaboub, N., M. V. A. Martins, A. Dhib, B. Béjaoui, F. Galgani, M. El Bour, and L. Aleya. 2015. Accumulation
1036 of trace metals in sediments in a Mediterranean Lagoon: Usefulness of metal sediment fractionation and
1037 elutriate toxicity assessment. *Environmental Pollution* 207: 226–237.
- 1038 Zaldívar, J., A. C. Cardoso, P. Viaroli, R. De Wit, C. Ibañez, S. Reizopoulou, A. Razinkovas, A. Basset, M.
1039 Holmer, and N. Murray. 2008. Eutrophication in transitional waters : an overview. *Transitional Waters*
1040 *Monographs* 1: 1–78.
- 1041 Zilius, M., G. Giordani, J. Petkuvienė, I. Lubiene, T. Ruginis, and M. Bartoli. 2015. Phosphorus mobility under
1042 short-term anoxic conditions in two shallow eutrophic coastal systems (Curonian and Sacca di Goro lagoons).
1043 *Estuarine, Coastal and Shelf Science* 164. Academic Press: 134–146.

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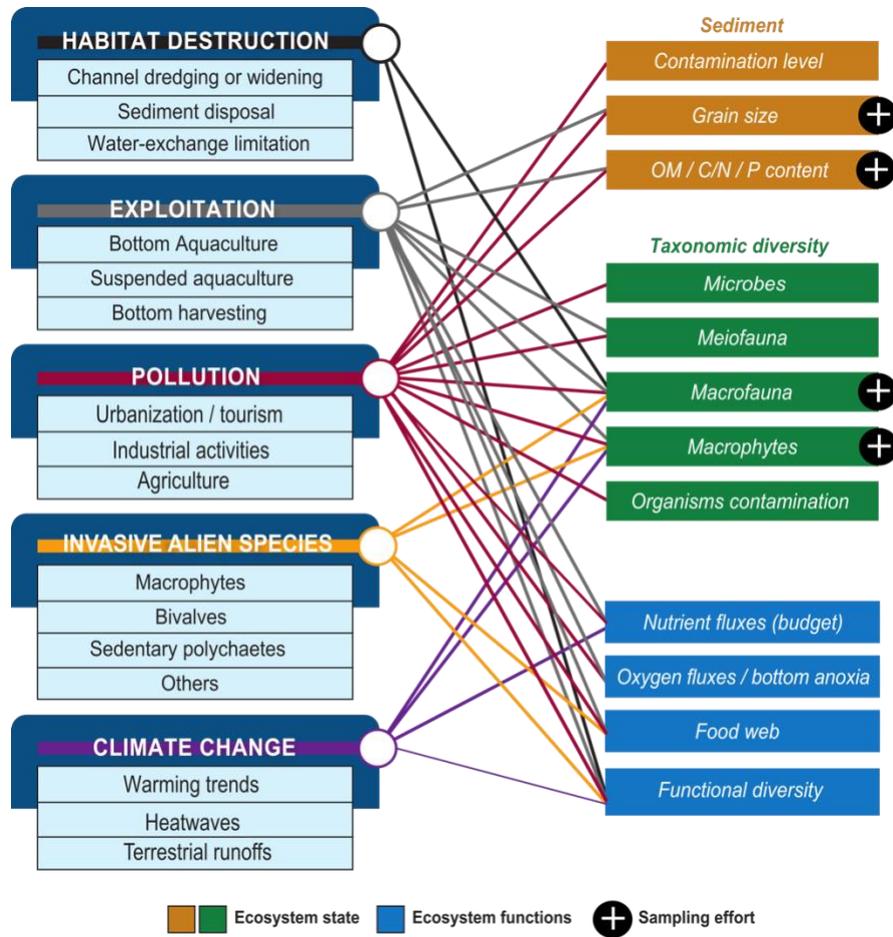
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Figure 1. The five main anthropogenic pressures potentially impacting coastal lagoon soft-bottom benthic ecosystems

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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 <u>Como and Magni 2009</u> <u>Dolbeth et al. 2003</u> Franzo et al. 2016 Jones et al. 2022 <u>Mahé et al. 2021</u> 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 <u>Le Fur et al. 2018, 2019</u> Marin-Guirao et al. 2005** <u>Pasqualini et al. 2017</u>	Jones et al. 2022 Nasi et al. 2018	Cibic et al. 2012 Franzo et al. 2016 <u>Rigaud et al. 2021</u> <u>Zilius et al. 2015</u>	<u>Carlier et al. 2009a</u>
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	Carlier et al. 2009b

				<p>Murphy et al. 2018 Nizzoli et al.2005, 2006b, 2007, 2011 Nizzoli et al. 2006a Schmidt et al. 2007 Thouzeau et al. 2007 Viaroli et al. 2003</p>	
<p>Invasive alien species (14)</p>	<p>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</p>	<p>Nonnis Marzano et al. 2003 Sfriso et al. 2012 Streftaris & Zenetos 2006</p>	<p>Munari 2008 Tlig-Zouari et al. 2011</p>	<p>Pranovi et al. 2006 Sfriso et al. 2020 Streftaris & Zenetos 2006</p>	<p>Carrozo et al. 2014 Como et al. 2018 Mancinelli et al. 2013, 2017 Marchessaux et al. 2021a,b</p>
<p>Climate change (9)</p>	<p>Canu et al. 2010 Ghezzi et al. 2018 Munari 2011 Mercurio et al. 2021</p>	<p>Lloret et al. 2008 Derolez et al.2020</p>	<p>Munari 2011 Pitacco et al. 2018</p>	<p>Harzallah & Chapelle 2002 Magri et al. 2020 Derolez et al. 2020</p>	