Climate change risks on key open marine and coastal Mediterranean ecosystems

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Abstract

Mediterranean open marine and coastal ecosystems face multiple risks, due to climate change, that impact their unique biodiversity. To assess these risks and evaluate their confidence levels, we adopt the scenario-based approach of the Intergovernmental Panel on Climate Change (IPCC), relying on a review of literature projecting changes in Mediterranean Sea ecosystems. The main drivers of environmental change are sea level rise, ocean warming and acidification. Similar to global conditions, all Mediterranean ecosystems face high risks under all climate scenarios, with coastal ecosystems being more strongly impacted than open marine ecosystems. For these coastal ecosystems, risk levels are expected to become very high already once global warming exceeds 0.8°C with respect to the 1976–2005 period. A few Mediterranean ecosystems (e.g., coralligenous and rocky coasts) have greater adaptive capacity than all others, probably because of the long evolutionary history in this sea and the presence of a variety of climatic and hydrological conditions. Overall, due to the higher observed and projected rates of climate change in the Mediterranean, compared to global trends, for variables such as seawater temperature and pH, marine ecosystems (particularly coastal) are projected to be under higher risks compared to the global ocean.

I. Introduction

The Mediterranean Sea is one of the most important regions in the world in terms of marine biodiversity and is home to more than 17000 marine species, almost 18% of all known marine temperate and subtropical species (Balzan *et al.* 2020). Among these species, ~ 20–30% are endemic (Coll et al. 2010), making it one of the main marine biodiversity hotspots of the world. Many key resident and transient marine organisms such as fish, shellfish, cetaceans (dolphins, whales) and top predators (tuna, swordfish) are ecologically and economically important. They play crucial roles in the food web and in supporting a variety of human activities, including tourism and fisheries, which are economically important (for income and employment) in most Mediterranean countries (MedECC 2020). Socio-economic and political disparities in the region are large and they influence the future development and management of Mediterranean ecosystems (Dos Santos *et al.* 2020; Hassoun et al. 2022).

Climate change, through changes in average as well as extremes in water temperature, pH and sea level, is one of the main drivers of risk for marine and coastal habitats worldwide (Henson et al. 2017; IPCC 2019). Due to its unique geological, climatic and hydrological features (Merheb et al. 2016; Balzan *et al.* 2020), the Mediterranean Sea is critically affected by climate change (Tanhua et al. 2013; Cramer et al. 2018; Chatzimentor *et al.* 2022; Álvarez et al. 2023). The projected additional impacts of climate change on marine and coastal ecosystems threaten the livelihoods of millions, as these ecosystems play a significant role in food security and coastal protection (Rice and Garcia 2011; Barange et al. 2018; IPCC 2022).

One of the most important drivers of regional ecosystem change is atmospheric warming which exceeds global mean values compared to the pre-industrial period, reaching ~ 1.5°C in 2020 (Cherif *et al.* 2020).

Regional warming will very likely continue to exceed the global mean value by 20% and may reach 5.6°C at the end of the 21st century under a high emission scenario (RCP8.5; Cos et al. 2022). Warming will be particularly strong in summer, likely to exceed the global annual rates by 50% (Lionello and Scarascia 2018). An accumulated warming of 1.3°C has been estimated for the Mediterranean Sea surface temperature (SST) from 1982 to 2019 (Pastor *et al.* 2020), less in the Western than the Eastern Mediterranean Basin with an increase rate that varies between + 0.29 to + 0.44°C decade^{-1} (Nabat et al. 2015; Darmaraki et al. 2019a; Pisano et al. 2020). For the period 1980–2020, the SST increase is more than 2-fold higher in the Mediterranean than globally (1.3°C in the Mediterranean *vs* 0.60°C globally; Fox-Kemper et al. 2021). The SST increase is strongest in the Eastern Basin, where some areas warmed up to + 1.2°C in the period 2000–2017 compared to 1980–1999 (Cherif *et al.* 2020). SST in the Mediterranean Sea is expected to increase by 0.6–1.3°C and 2.7–3.8°C by 2050 and 2100, under the RCP4.5 and RCP8.5 scenarios, respectively (Darmaraki et al. 2019b). Intermediate and deep-sea temperature and salinity (below 400 m) are also significantly increasing (Vargas-Yáñez et al. 2010; Skliris et al. 2014; Schroeder et al. 2016). By the end of the century, the projected temperature change ranges are 0.81–3.71°C in the upper layer (0–150 m), 0.82–2.97°C in the intermediate layer (150–600 m) and 0.15–0.18°C in the deep layer (600 m-bottom), strongly depending on the adopted scenarios and global forcing (Soto-Navarro et al. 2020).

Marine heat waves are projected to become longer, more intense, and more frequent (Darmaraki et al. 2019a; Garrabou et al. 2022; Juza et al. 2022; Pastor and Khodayar 2022; Dayan et al. 2023). Although the intensity of precipitation extremes is projected to increase in some areas of the Northern Mediterranean (Tramblay and Somot 2018; Lionello and Scarascia 2020; Cos et al. 2022), total annual precipitation is expected to decrease over most of the basin (the average reduction rate is approximately 4% per each degree of global warming) under RCP8.5 (Lionello and Scarascia 2018; Cherif *et al.* 2020).

Warming directly modifies the ocean’s thermal stratification (Powley et al. 2016), potentially increasing eutrophication and dissolved oxygen (O_2) consumption due to increasing dissolved organic carbon concentrations in the mixed layer (Ferreira et al. 2011; Santinelli et al. 2013; Ngatia et al. 2019). Increasing atmospheric CO_2 results in acidification of both surface and deep waters (Hassoun et al. 2022). Ocean acidification of Mediterranean waters (upper 80 m) occurs at rates of -0.001 to -0.009 pH units y^{-1} depending on regions (Eastern *vs.* Western basin) and time period (Hassoun et al. 2022). By the end of the current century, pH is expected to drop 0.28 to 0.462 pH units below the pre-industrial values depending on scenarios, with some differences between sub-basins and depths (Goyet *et al.* 2016; Hassoun et al. 2022; Reale et al. 2022; Solidoro et al. 2022). This pH decrease is ~ 1.5-fold more pronounced than the average global ocean (~ 0.3–0.4 units by the year 2100; Kwiatkowski et al. 2020), according to most pessimistic scenarios (Reale et al. 2022; Solidoro et al. 2022). Some Mediterranean sub-basins might experience more exacerbated acidification trends than the global ocean in the future (Hassoun et al. 2015; 2022; Álvarez et al. 2023).

Sea level rise (SLR) has major consequences on coastal ecosystems including more frequent and/or intensive flooding along low-lying coasts, particularly in deltas and lagoons, wetlands, and some islands

(McFadden et al. 2007, Balzan *et al.* 2020), and coastal erosion (Satta *et al.* 2017; Ali *et al.* 2022). During inundations and storm surges, SLR affects coastal infrastructures and coastal communities. Sea level has risen at a rate of about 1.2–1.3 mm yr^{-1} since the end of the 19th century (Zerbini et al. 2017) and of 1.7 mm yr^{-1} since the mid-20th century (Wöppelmann and Marcos 2012), similar to the global trend, increasing to about 2.57 mm yr^{-1} since 1993 (based on satellite altimetry, Marcos et al. 2023). Mediterranean sea level is projected to be 20 to 110 cm higher at the end of the 21st century compared to the 2000s (Cherif *et al.* 2020), and will likely be similar to the global rates because regional differences produced by changes in the circulation and mass redistribution almost compensate each other (Slangen *et al.* 2017).

The sum of climate change-related habitat alterations, in association with non-climatic stressors, pose unprecedented risks for the Mediterranean Sea biodiversity and resilience, potentially driving many species outside the conditions required to acclimate or adapt. Key open marine and coastal ecosystems are already impacted, threatening their diversity, as well as the services and resources they provide (Liquete et al. 2016; Martín-López et al. 2016). These risks faced by the Mediterranean Sea open marine and coastal ecosystems need to be well defined to understand the implications on the health and viability of its key species. Here, we present an integrated overview of the main risks that are threatening key Mediterranean open marine and coastal ecosystems. We build on the assessment performed using expert judgment conducted in the preparation of the MedECC report (Balzan *et al.* 2020) to evaluate the responses of key habitats and ecosystems, towards various climate change risks under multiple climate change scenarios by the end of the 21st century.

II. Methods

II.1. General approach

This study addresses both the open Mediterranean Sea and its coastal zone. Many definitions exist to determine the spatial extent of the coastal zone. Here, we define the coastal zone as the area up to an elevation of 10 m above mean sea level (i.e. “Low-Elevation Coastal Zone” LECZ, a term used in sensitivity studies with respect to the projected sea level rise; Vafeidis et al. 2011; MedECC 2020). The coastal ecosystems here include sandy beaches and sand dunes, rocky coasts, coastal lagoons and deltas, salt marshes and coastal aquifers (Fig. 1). Open marine ecosystems comprise epipelagic ecosystems, coralligenous, seagrass meadows, fish, seaweeds and megafauna (Fig. 1). For simplification, we use the term “ecosystems” to encompass ecosystems *sensu stricto*, habitats and/or key biological groups. The detailed definition of each ecosystem is provided in Supplementary Material (S1).

A literature review was conducted, searching for peer-reviewed publications that highlight projections for any of the ecosystems of interest (Fig. 2). Risk levels for biodiversity loss under various warming scenarios for six open marine ecosystems and six coastal ecosystems were developed and visualized through “burning embers”, a widely-used qualitative IPCC plot featuring risk levels (‘Undetectable’, ‘Moderate’, ‘High’, ‘Very high’). Based on the levels of evidence and agreement, a confidence level has been assigned to each projected risk (Mastrandrea *et al.* 2010).

II.2. Data compilation

Our literature review covered 196 publications (until August 2023) compiled using academic search engines (Google Scholar, Scopus and ResearchGate) to capture all available studies projecting changes in Mediterranean Sea ecosystems (Fig. 2). The searched keywords comprised the following terms: projections, forecasts, scenarios, Mediterranean Sea, with variable keywords depending on the ecosystem we were looking for (e.g., corals, fish, seaweeds, etc.). After assessing these papers, we only kept the ones that have clearly identified scenario projections (N = 131), the other publications were used as additional resources for discussion (Fig. 2).

Data extracted from these studies comprise the emission scenarios used, the timing of the projections (mid- and/or end of the century), and other parameters taken into consideration to implement the projections (e.g., global atmospheric temperature, Mediterranean atmospheric temperature, seawater temperature, pH, SLR, etc.; see section II.3), the estimated risk(s), confidence level and the main drivers if available. Additional information was extracted from all relevant papers, such as the affiliation country of the first author, the study area, and the type of the study (i.e., modeling, laboratory experiment, mesocosm experiment, in situ study, observations near CO_2 vents, remote sensing, review, etc.) (see Supplementary Material S2 for additional information). The locations of the study areas are shown in Fig. 3.

The publications assessed (N = 131) have very large geographical disparities in terms of the type of studies and study sites (Fig. 3); they also have unequal distribution across habitats. Only 11 were conducted in non-European (outside the European Union) Mediterranean countries. Italy, France, and Spain account together for 73 articles (56% of all studies). This disparity is reflected in the distribution of study sites across the Mediterranean Sea. In fact, 43 out of 50 open marine ecosystems sites and 51 out of 66 coastal sites are located in European countries. This results in a strongly biased distribution of study areas between the different Mediterranean Sub-basins, since most European countries are located in the Western realm of the Mediterranean Sea. Even for regional studies that address the various parts or the entire Mediterranean Sea (n = 36), 30 studies are led by researchers from Northwestern Mediterranean countries. Regional studies favor open marine ecosystems (32 out of 36). Overall, research in the Southern and Eastern Mediterranean marine and coastal areas is relatively scarce.

Not all ecosystem types could be investigated equally. Among the 116 study sites, 66 are coastal (57%), while the remaining 50 are open marine ecosystems. The most studied open marine habitats are the epipelagic with 16 study sites and 11 regional studies, followed by fish (7 sites and 11 regional studies), and coralligenous (17 sites and one regional study). Seagrass meadows, seaweeds, and megafauna are largely understudied with only 11, 3, and 4 study areas respectively. Only one study could be found for the deep-sea. As for coastal ecosystems, a large disparity also exists in terms of studied habitats. Sandy beaches and sand dunes are the most studied with 21 sites, followed by lagoons and deltas (15 sites and one regional study), and rocky coasts (10 sites and one regional study). Coastal aquifers, coastal wetlands and salt marshes account for 9, 8, and 5 studies respectively.

There is a disparity in the source of data used. By necessity, assessments of future conditions in most ecosystems cannot be observed – they are therefore based on well-constrained ecological model simulations. Specific local conditions in coastal ecosystems are often derived from remote sensing, while process understanding applied to the assessment is based on laboratory or in-situ experiments. Ecological model simulations are the main source for open marine ecosystems, while remote sensing is the most common for coastal ecosystems. The number of coastal ecosystem studies using modeling is also high (Fig. 4). Studies based on *in situ* observations are very scarce for both open marine and coastal ecosystems. Furthermore, the number of experimental studies for open marine ecosystems is relatively high (14 lab. Experiments and 7 mesocosms), there are only 4 experimental studies for coastal ecosystems. The majority of experimental studies are conducted in the Northwestern Mediterranean.

The detailed approach used to convert global scenarios into Mediterranean ones, to assign risks and confidence levels used to visualize the risks in Fig. 5 are all detailed in the Supplementary Material (S3). Risk levels and risk drivers with respect to the preindustrial values were also calculated, visualized and presented in S4. Finally, a comparison between risk levels in the Mediterranean vs the ones in the global ocean are detailed in S5.

III. Results and discussion

III. 1. Mediterranean key habitats undergoing change

Our assessment shows that severe risks on biodiversity, structure and function of coastal ecosystems are projected to be higher than for open marine ecosystems (high confidence) when Mediterranean Sea surface warming exceeds 1ºC above the reference period 1976–2005, combined with other climate-related hazards. Most coastal ecosystems assessed are projected to face an increasing risk level, from moderate to high under 2°C ΔSST warming to high to very high above 2°C relative to 1976–2005 (Fig. 5). The only exception is the “Rocky Coasts”, being relatively the least vulnerable. The main stressor for coastal ecosystems is linked to exposure to SLR (Fig. 6). This reflects the remarkable risks for coastal habitats posed by climate change in addition to those caused by anthropogenic pressures.

Among the open marine ecosystems, seagrass meadows and seaweeds will face the most severe risks while the least impacted will be the epipelagic (low to medium confidence level). The main stressors for the open marine ecosystems are predominantly linked to exposure to ocean warming and ocean acidification (Fig. 6).

Open marine ecosystems:

Epipelagic

Most studies highlight ocean warming as the main driver (Lazzari et al. 2014; Maugendre et al. 2015; Pulina et al. 2016; Gazeau *et al.* 2017; Benedetti *et al.* 2018; Moltó et al. 2021; Reale et al. 2022; Solidoro et al. 2022), with risks projected to be undetectable to moderate under $+0.8°C < \Delta SST < +6°C$ (medium confidence) (n = 12; Fig. 5). Ocean acidification is the second most relevant driver (Gazeau *et al.* 2017; Maugendre *et al.* 2017; Reale et al. 2022) (Fig. 5). Other less significant drivers include changes in ocean stratification/circulation (Herrmann et al. 2014; Macias et al. 2015), changes in salinity (Benedetti *et al.* 2018; Stefanidou et al. 2018), nutrient enrichment (Reale et al. 2022), deoxygenation (Reale et al. 2022), atmospheric CO_2/acidification (Solidoro et al. 2022), and solar radiation (Moltó et al. 2021) (Fig. 6).

Ocean warming is expected to increase gross primary production, boosting phytoplankton exudation and bacterial growth. The planktonic community structure is generally expected to shift towards larger biomasses of small-size groups (Herrmann et al. 2014; Maugendre et al. 2015; Pulina et al. 2016; Gazeau *et al.* 2017; Moullec et al. 2019; Pagès *et al.* 2020; van Leeuwen et al. 2022), particularly pico- and nanophytoplankton, and bacteria (Herrmann et al. 2014). However, studies indicating an undetectable to moderate risk also highlight that the abundance of relatively large phytoplankton species (e.g., *Cyclotella* sp. and *Thalassiosira* sp.) is expected to decline due to warming, potentially decreasing the export and energy transfer to higher trophic levels, with a very limited impact from ocean acidification/increasing pCO_2 (Maugendre et al. 2015; 2017; Pulina et al. 2016; Gazeau *et al.* 2017; van Leeuwen et al. 2022). Other studies (n = 11) demonstrate higher risks on epipelagic species (although with lower confidence levels). For example, ocean warming is expected to boost the expansion of Harmful Algal Blooms (HABs, e.g., *Ostreopsis ovata*) and thermophilic and/or exotic species of smaller size and of low trophic levels, which might produce biotoxins, a serious public health hazard (Accoroni et al. 2016; Vila et al. 2016; Abboud-Abi Saab and Hassoun 2017; Moullec et al. 2019; Pagès *et al.* 2020; Hassoun et al. 2021). Changes in species richness are also projected due to increasing temperature (predominantly during marine heat waves; Soulié et al. 2023) and changes in ocean stratification/circulation (Howes et al. 2015; Macias et al. 2015). Additional factors are expected to change and consequently modify the epipelagic ecosystems, such as changes in nutrient concentrations (e.g., nitrite and nitrate concentrations are expected to decrease mainly due to rising temperatures and decreasing continental inputs; Temino-Boes et al. 2021), weakened winter convection, surface layer warming and the changing variability of extreme meteorological events (Herrmann et al. 2014; Totti et al. 2019).

In combination, these changes are expected to modify the seasonal blooms, as spring blooms may occur earlier (Volpe et al. 2012; Herrmann et al. 2014) and last longer (Macias et al. 2018). Calcifiers, such as foraminifera, pteropods and coccolithophores, are among the most vulnerable organisms to combined warming and acidification effects impacting surface ocean stratification and food availability (Meier et al. 2014; Mallo et al. 2017; D’Amario et al. 2020). Epipelagic harvested species (e.g., fish, macroinvertebrate, cephalopods) are projected to significantly change in terms of stocks and distribution, mainly due to ocean warming (Moullec et al. 2019; Schickele et al. 2020; 2021; Moltó et al. 2021; van Leeuwen et al. 2022). Overall, these contradictory findings reflect the specificities of sub-regions and drivers taken into consideration. Mediterranean basins and sub-basins will likely face nonuniform future risks, i.e., on primary production and species diversity (Benedetti *et al.* 2018; Richon et al. 2019; Pagès *et al.* 2020; Reale et al. 2022; Solidoro et al. 2022).

Coralligenous

Risks here are projected to be undetectable to moderate below ΔSST = + 3.1°C (low confidence) and moderate to high (medium confidence) above ΔSST = + 3.1°C (n = 10; Fig. 5). Most of the studies highlight acidification as the main driver (Hall-Spencer *et al.* 2008; Martin and Gattuso 2009; Movilla et al. 2012; Bramanti et al. 2013; Movilla *et al.* 2014; Fine *et al.* 2017; Prada *et al.* 2017; Marchini et al. 2020), followed by warming (Martin and Gattuso, 2009; Fine *et al.* 2017; Prada *et al.* 2017; Marchini et al. 2020; Vitelletti *et al.* 2023) (Fig. 6). Other drivers were also mentioned, such as changes in salinity (Vitelletti *et al.* 2023), nutrient enrichment (Vitelletti *et al.* 2023), and marine heat waves (Gómez-Gras et al. 2019) (Fig. 6). Most coralligenous species will undergo change but appear to be unlikely to disappear with a warming climate, contradicting earlier projections (Hassoun et al. 2022). Above + 3.1°C, ocean acidification impacts recruitment and growth of the early life stages of corals like *Astroides calycularis* (Carbonne *et al.* 2022), and is expected to alter typical rocky shore communities that will lack scleractinian corals and reduce the abundance of sea urchin and coralline algae (Hall-Spencer *et al.* 2008). Zooxanthellate coral species like *Cladocora caespitosa* and *Oculina patagonica*, and some cold-water coral species such as *Desmophyllum dianthus* will also face detrimental effects due to ocean acidification (Movilla et al. 2012; 2014). The Mediterranean red coral *Corallium rubrum*'s skeletal growth and spicule morphology could be detrimentally affected by low pH (Bramanti et al. 2013). In synergy with ocean acidification, ocean warming will also have impacts on some corals (Carbonne *et al.* 2022). Calcifying algae living near their thermal limit are likely to be threatened by ocean acidification and may not be able to contribute to reef accretion under the projected levels of warming and acidification (Fine *et al.* 2017). Mortality of coralline algae, particularly *Lithophyllum cabiochae*, is also expected to increase with net dissolution surpassing net calcification (Martin and Gattuso 2009). Also, synergistic effects on mortality rates are expected to affect all Mediterranean scleractinian corals (up to 60%), suggesting that high seawater temperatures may have increased their metabolic rates which, in conjunction with decreasing pH, can lead to rapid deterioration of cellular processes and performance (Prada *et al.* 2017).

Although the 10 studies used in our risk assessment diagram present concordant conclusions regarding the response of many coralligenous species to climate change effects, the rest of the assessed literature presents some ambiguities and contradictory results. Some coralligenous species are expected to show no physiological (Martin et al. 2013) or mineralogical (Nash et al. 2016) changes, even under high emission scenarios. For example, after several months of exposure to acidified conditions, the skeletal growth rate of *Dendrophyllia cornigera* showed no difference with control conditions (Movilla *et al.* 2014). Under low pH conditions, some species of crustose coralline algae become more resistant while others are becoming more sensitive (Kamenos *et al.* 2016). *Ellisolandia elongata* may withstand projected temperature changes (Nannini et al. 2015; Gamliel et al. 2020), counteracting the effect of combined stressors (acidification and warming), although these stressors may cause shifts in the associated assemblages toward a less diverse structure, with possible dominance of the more opportunistic species (Marchini et al. 2019). Coverage of invertebrate calcifiers and crustose coralline algae appears not to be affected by the lowered pH (Cox *et al.* 2017). Environmental variations (e.g., salinity, temperature, and nitrate concentration) under climate change conditions are expected to favor opportunistic organisms at the expense of vulnerable species in coralligenous habitats, potentially leading to biodiversity loss in certain regions, such as in the Northern Adriatic Sea (Vitelletti *et al.* 2023).

The diversity of responses to climate change drivers reflects the complexity of this ecosystem and points out species-specific responses, suggesting the presence of potential winners and losers (Gómez-Gras et al. 2019).

Seagrass meadows

Risks are projected to be high to very high with ΔSST = + 0.8°C (medium confidence) (n = 5; Fig. 5). Seagrass meadows are among the main Mediterranean ecological key ecosystems projected to face significant climate-related risks. Seagrass species' responses to warming are complex, due to varying thermal performance. While some meadows exhibit thermal resilience, others suffer population declines. Under high CO_2/low pH conditions, macroalgal communities undergo shifts with dominant species changing, while some species exhibit enhanced reproduction (Porzio et al. 2011). Ocean acidification contributes to changes in benthic communities, altering competitive dynamics between calcareous and fleshy seaweeds (Porzio et al. 2013). Projections for some seagrass species are showing generally negative results. Although negative impacts from ocean acidification on *Posidonia oceanica* epiphytic communities are projected to be smaller than previously expected (Cox *et al.* 2017), *P. oceanica* might still lose 75% of suitable habitats by 2050 and is at risk of functional extinction by 2100 under high warming scenarios, as genetic diversity erosion and habitat loss are expected (Chefaoui et al. 2018), specifically in the Eastern Mediterranean (Litsi-Mizan *et al.* 2023). Other studies are projecting functional extinction of *P. oceanica* by mid-century, even under relatively mild GHGs emissions (Jordà *et al.* 2012). Seagrass shoot mortality rates and losses are projected to increase with rising temperatures (Marbà and Duarte 2010), and younger life stages (i.e., seedlings of *P. oceanica*) may be particularly vulnerable (Balzan et al. 2020).

Warming in areas with excessive nutrient and organic inputs may exacerbate the risk for sediment anoxia and production of metabolites as sulfides, both detrimental for seagrass survival (Jordà *et al.* 2012). These results have been confirmed in a recent study (Llabrés et al. 2023), projecting that *P. oceanica* meadows will experience a 70% population decline by mid-century giving way to the more resilient *Cymodocea nodosa*. Joint effects of warming and eutrophication are projected to further curtail the survival of *C. nodosa* (Ontoria et al. 2019). Warming and acidification drive shifts in seagrass morphology, impacting seagrass shoot morphology and reproductive strategies and altering leaf and rhizome morphology which will affect nutrient storage, trophic interactions, and meadow resilience (Stipcich et al. 2022). In addition, the joint effect of low light, increased turbidity, changes in water circulation, nutrients' availability, and ocean warming may play a major role in the survival of *P. oceanica*, regardless of the genetic traits (Martínez-Abraín et al. 2022) and the possible benefits from increased

$p\mathrm{CO}_2$ (Hendriks et al. 2017). Otherwise, more suitable habitats could become available for both tropical species, *Halophila stipulacea* and *H. decipiens*, during this century under all RCP scenarios (Beca-Carretero et al. 2020). The predicted rapid expansion of these non-native species could alter the Mediterranean's seagrass community and may have significant socio-economic consequences.

Fish

Risks here are projected to be undetectable to moderate below ΔSST = + 0.8°C (low confidence) and moderate to high (medium confidence) above ΔSST = + 0.8°C (n = 8; Fig. 5). Most studies identify ocean warming as the main driver of change (Moullec et al. 2019; D'Amen and Azzurro 2020; Stavrakidis-Zachou et al. 2021; Ben Lamine *et al.* 2022; Lima et al. 2022; Tsagarakis et al. 2022; van Leeuwen et al. 2022; Loya-Cancino et al. 2023), followed by invasive species (Dimitriadis et al. 2020; D'Amen and Azzurro 2020; Loya-Cancino 2023) (Fig. 6). These studies are mainly predicting a significant fish stock reduction (~ 30% for RCP4.5 and ~ 40% for RCP8.5; van Leeuwen et al. 2022) together with a contraction of the distributional range of commercial species, with a general biogeographical displacement towards North European coasts (Ben Lamine *et al.* 2022). This is in agreement with studies forecasting the shifts in suitable spawning habitats in all seasons to higher latitudes caused by warming and decreased plankton productivity affecting sardine stocks (Lima et al. 2022). Higher temperatures are expected to boost the suitable areas for invasive species, even in protected areas, predominantly in the Eastern Mediterranean and to a lesser extent in the South Adriatic Sea and off South-West Italy (D'Amen and Azzurro 2020). For example, suitable conditions for the lionfish, *Pterois miles*, are likely to expand to the Northern and colder areas even under mild warming scenarios (Loya-Cancino et al. 2023). Ocean warming might slow down the deep overturning circulation, affecting the stratification of the water column and thus the nutrient supply and primary production which are projected to impact some species in additive (sardines) or synergistic ways (anchovy, mackerel) (van Leeuwen et al. 2022). More severe risks are projected by other studies (n = 3), predicting a significant loss of climatically suitable habitats for endemic species (Albouy et al. 2013) with climate-related local extinctions of the most harvested small pelagic species in Europe, mainly in the South-Eastern Mediterranean (Schickele et al. 2020), and a considerable expansion of *Pterois miles* towards new areas (Dimitriadis et al. 2020). In contrast, other studies (n = 4) indicate only undetectable to moderate risks. These studies mostly predict an increase of suitable areas/gains (e.g., for anchovy spawning habitats), total biomass, total length at catch, total catch with some spatial and inter-species contracts with increases mainly projected in the Eastern Mediterranean and the Iberian Peninsula (Moullec et al. 2019; Maynou et al. 2020; Moltó et al. 2021; Lima et al. 2022) in parallel with potential distribution shifts northward (e.g., round sardinella; Maynou et al. 2020).

Seaweeds

Risks here are projected to be undetectable to high below ΔSST = + 0.8°C (low confidence) and high to very high (low confidence) above ΔSST = + 0.8°C (n = 2; Fig. 5). These studies identify ocean warming (Samperio-Ramos et al. 2015; Buonomo et al. 2018), followed by invasive species (Samperio-Ramos et al. 2015) as main drivers (Fig. 6). The main risks include diversity loss (e.g., of *Cystoseira* macroalgae) due to habitat retractions and genetic erosion, mostly in the Eastern Mediterranean Sea (Buonomo et al. 2018). This loss could have cascading effects on the whole ecosystem and its services (Thrush et al. 2011; Araújo *et al.* 2016). Projections include triggering high abundance of invasive seaweeds in coastal areas (e.g., *Acrothamnion preissii*, *Lophocladoa lallemandii* and *Caulerpa cylindracea*), accelerating the decline of already threatened native habitats, such as seagrasses (Marbà and Duarte 2010) and gorgonians (Coma et al. 2009). This process can be attributed to the reduction in biotic resistance of native communities to the arrival of non-indigenous seaweeds (Samperio-Ramos et al. 2015). Another study, not taken into consideration in our risk assessment as it has low confidence level, reflects more complex projections showing that climate-induced range shifts may be less drastic and thus most species are unlikely to completely disappear (e.g., *Padina pavonica, Halopteris scoparia*; Gamliel et al. 2020). These results suggest marked differences in warming sensitivity within and between benthic communities (Bennett et al. 2022).

Megafauna

Risks are projected to be undetectable to moderate below ΔSST = + 3.1°C (low confidence) (n = 3; Fig. 5). These studies are overwhelmingly stating ocean warming as the main driver (Almpanidou et al. 2019; Chatzimentor et al. 2021; Albouy et al. 2020; Fig. 6). The main risks include a disproportionate loss of functional diversity (Albouy et al. 2020), an increase in the daily energy expenditure and thus an alteration of the physiological functions of marine turtles (Almpanidou et al. 2019) with contractions of their foraging space (Chatzimentor et al. 2021). There is low confidence in the identification of these risks as foraging areas are likely to increase by up to 10%, mainly in neritic zones (Chatzimentor et al. 2021). Overall, megafauna-related projections are very limited in the Mediterranean. Already observed changes include a poleward shift and an alteration of the migration timing for some cetaceans (van Weelden et al. 2021). While expected risks encompass megafaunal range shifts for some species (such as the westward shifts of loggerhead turtles; Mancino *et al.* 2022) and extinction for others (such as the common dolphins *Delphinus delphis*; Santostasi *et al.* 2018). 21–31% of Mediterranean marine ecoregion species have high climate risk (Chatzimentor et al. 2023), increasing the risk of extinction of critical species even in protected areas. While fin whales can leave the Western Mediterranean Sea through the Strait of Gibraltar, the 12 Hellenic Trench cetacean species (Frantzis *et al.* 2003) are surrounded by much shallower seas that make it difficult to leave (Grose et al. 2020). In addition, Mediterranean-wide shifts in prey distribution and abundance driven by climate change and anthropogenic disturbance is expected for the black anglerfish (Haubrock *et al.* 2020).

Coastal Ecosystems:

Sandy beaches and sand dunes

Risks are projected to be undetectable to high below ΔSST = + 0.8°C (low confidence) and high to very high (high confidence) above ΔSST = + 0.8°C (Fig. 5). SLR is by far the dominant driver (Fig. 6) (Enríquez *et al.* 2017; Monioudi *et al.* 2017; Rizzi *et al.* 2017; Sanuy et al. 2018; Varela et al. 2019; Antonioli et al.

2020; Anzidei *et al.* 2021; Thiéblemont et al. 2021; Rizzo et al. 2022; Filippaki et al. 2023; Vandelli et al. 2023; Monioudi et al., 2023). Other drivers include storm surges (Rizzi *et al.* 2017; Monioudi et al., 2023), changing precipitation and warming (Prisco et al. 2013) (Fig. 6). The major risks of SLR are shoreline retreat and coastal inundation. Modeling results project very severe erosion and floodings from as early as mid-century particularly under the combined effects of the projected mean SLR and storm surges (Enríquez *et al.* 2017; Monioudi *et al.* 2017; Sanuy et al. 2018; Antonioli et al. 2020; Anzidei *et al.* 2021; Thiéblemont et al. 2021; Rizzo et al. 2022; Vandelli et al. 2023; Monioudi et al., 2023). Due to their low elevation and proximity to the sea, sandy beaches are at higher risk (Rizzi *et al.* 2017; Sharaan and Udo 2020; Filippaki et al. 2023; Sánchez-Artús et al. 2023) compared to dunes (Sanuy et al. 2018). The transition dune habitat is projected to remain stable, although mobile and fixed dune habitats are projected to lose most of their actual distribution, the latter being more sensitive to climate change effects. The partial or total destruction of sandy beaches and dune habitats seriously threatens species and biodiversity hampering these ecosystems' resilience (Scapini et al. 2019). For example, a SLR of 1.2 m is expected to cause a loss of 67.3% and 59.1% for loggerhead and green turtle nesting sites respectively (Varela et al. 2019). The specificity of sandy beaches as narrow ecotones between sea and land may be lost, adversely affecting fine-tuned macrofaunal adaptations and therefore ecosystem functioning (Scapini et al., 2019).

Rocky coasts

Risks are projected to be undetectable to moderate below $\Delta SST = +0.8°C$ (low confidence) and moderate to high (medium confidence) above $\Delta SST = +0.8°C$ (Fig. 5). SLR is the major driver (Fig. 6) (Antonioli et al. 2020; Rilov et al. 2021; Bonello et al. 2022; Lo Presti et al. 2022; Rizzo et al. 2022). Other drivers are ocean warming (Bonello et al. 2022) and acidification (Milazzo et al. 2014) (Fig. 6). Compared to other coastal ecosystems, SLR-related risks seem to be lower for ΔSST above $+0.8°C$, mostly because the elevation of these areas is a critical factor (Antonioli et al. 2020; Rizzo et al. 2022). Nevertheless, some of these habitats may undergo serious deterioration under the projected SLR for mid- and end of the century, such as in North-Eastern Sicily that may undergo gravity collapse events (Lo Presti et al. 2022). The deterioration and inundation of these habitats will affect the resident populations, as biodiversity is shown to be much lower on very shallow, permanently submerged, horizontal rocky surfaces compared to the one on intertidal reef platforms (Rilov et al. 2021). The rich intertidal community will shift, when permanently submerged, either to a very different but still rich community when protected from grazing or to a much poorer turf community when exposed, and the reef community net production will drastically drop (Rilov et al. 2021). Also, insects are expected to be impacted. For instance, the splashpool resident culicid *Acartomyia mariae* will be affected by SLR and warming since its life cycle is highly dependent on temperature and salinity (Bonello et al. 2022), posing a sanitary risk with implications for human activities and subsequent coastal management. Ocean acidification will also impair vermetid reef recruitment, especially the pH sensitive gastropods. Unless CO_2 emissions are reduced and conservation measures taken, results suggest that these reefs are in danger of extinction (Milazzo et al. 2014). High risks are projected for the occurrence of *patellids* in 2050 and 2100 (Freitas et al. 2023), as these species are predicted to decline in the South and progressively expand their ranges further North.

Coastal wetlands

Risks here are projected to be high to very high above ΔSST = + 0.8°C (high confidence) (n = 6; Fig. 5), mainly affected by SLR (Rizzi et al. 2016; 2017; Mastrocicco *et al.* 2019; Antonioli et al. 2020; Estrela-Segrelles et al. 2021) (Fig. 6). Other drivers are related to changing precipitation (Ramírez et al. 2018; Lefebvre et al. 2019), seawater intrusion (Mastrocicco *et al.* 2019), and storm surges (Rizzi *et al.* 2017) (Fig. 6). In general, more exposure to coastal hazardous events are projected, affecting not only wetlands but also the densely inhabited settlements and infrastructures in their vicinity (Antonioli et al. 2020). These risks are predicted to negatively affect waterbird communities, mainly the ones residing and breeding in these wetlands as environmental suitability will decline (Ramírez et al. 2018). On the other hand, small wading birds may benefit from changing conditions, mainly the ones who use the affected wetlands for wintering or stopover, as most wintering species use muddy areas and open water to forage and will likely benefit from increasing water salinity and the decline in aquatic vegetation (Ramírez et al. 2018). Other studies project that increased salt and sulfide concentrations may induce physiological stress in wetland biota and ultimately result in significant shifts in wetland communities and their associated ecosystem functions (Herbert *et al.* 2015). For example, salinity changes can significantly alter crustacean communities hatching from the resting egg bank and negatively affect the establishment of large branchiopods and copepods. This might shift the whole wetland regime from a zooplankton-rich clear-water state to a zooplankton-poor turbid state, altering the structure and diversity of invertebrate communities, including some keystone species (Waterkeyn *et al.* 2010).

Coastal lagoons and deltas

Risks here are projected to be high to very high starting from a ΔSST = + 1.0°C (high confidence) (n = 9; Fig. 5). SLR is by far the major driver affecting these ecosystems (Ben Haj et al. 2009; Shaltout et al. 2015; Antonioli et al. 2020; Lionello et al. 2021; Filippaki et al. 2023) (Fig. 5). Other drivers include changing precipitation (La Jeunesse et al. 2015), terrestrial runoff (La Jeunesse et al. 2015), nutrient enrichment (Lloret et al. 2008), and marine heat waves (Soulié et al. 2023) (Fig. 6). The predicted impacts include a remarkable increase of SLR (e.g., up to 160% in 2100 in the Northern Adriatic; Lionello et al. 2021), causing floodings (Shaltout et al. 2015) and loss of important habitats nesting beaches, i.e., for the loggerhead (*Caretta caretta*), such as in the Egyptian coasts/Nile delta region (Ben Haj et al. 2009). These effects are expected to have significant environmental and socioeconomic consequences, as many lagoons and deltas will be highly vulnerable (Filippaki et al. 2023). In addition, risks include drier soil moisture conditions, negative effects on water quality comprising anoxic crises, intensified terrestrial storm runoff, providing coastal ecosystems with large nutrient pulses and increased turbidity, with unknown consequences for the phytoplankton community (La Jeunesse et al. 2015). These latter are expected to witness an altered natural succession due to heat waves, as cyanobacteria and chlorophytes are favored at the expense of haptophytes (Soulié et al. 2023). Also, it is predicted that

Caulerpa prolifera, that is significantly uptaking nutrients avoiding thus the occurrence of high phytoplankton densities, will be negatively affected, worsening eutrophication (Lloret et al. 2008). Otherwise, high to very high risks with low confidence level include more coastal hazards, causing significant loss of coastal lands (Antonioli et al. 2020) and continuous shoreline erosion (Abd-Elhamid et al. 2023). Undetectable to moderate risks attributed to SLR are also expected in specific areas such as the Ebro Delta (Sánchez-Arcilla et al. 2008) with relatively higher rates in the Eastern Mediterranean Sea (e.g., Egypt) compared to its Western part (Sharaan and Udo 2020). Moderate risks are forecasted for macroinvertebrates in coastal lagoons due to ocean acidification (Range et al. 2014). Other studies are expecting less drastic effects on the zooplankton community, with even positive influence, although their structure will be subjected to changing competitive interactions (Simantiris and Avlonitis 2023). Other studies (not included in our analysis as they do not present projections) show site-specific impact combinations (Day et al. 2019). In addition to the increasing vulnerability due to SLR (Frihy and El-Sayed 2013), an alteration of phytoplankton blooms is projected, as shallow coastal ecosystems shift towards famine or feast dynamics (Deininger et al. 2016). Human activities are expected to worsen the projections due to natural habitat destruction and alteration of the hydrological cycle (e.g., Cardoch et al. 2002).

Salt marshes

Risks are projected to be high to very high above ΔSST = + 0.8°C (medium confidence) (n = 5; Fig. 5), with SLR as the main driver (Antonioli et al. 2020; Anzidei *et al.* 2021; Scardino *et al.* 2022) (Fig. 5). Other drivers also include atmospheric warming, precipitation change (Strain et al. 2017), and invasive species (Borges *et al.* 2021) (Fig. 6). The risk of SLR was mostly assessed along the Italian coasts (Sicily and coastal areas of the Adriatic Sea; Antonioli et al. 2020; Anzidei *et al.* 2021; Scardino *et al.* 2022). Projections show important flooding in mid- and end of the century resulting in habitat submersion. This change is expected to be accelerated by natural and anthropogenic land subsidence in some areas (Anzidei *et al.* 2021; Scardino *et al.* 2022). Risk maps for other low-lying areas, involving several islands (Sardinia, Elba Island in Italy; Corsica in France; Cyprus; Kerkennah in Tunisia; Majorca and Ibiza in Spain), provide an estimated potential land loss of about 150 km^2 for the RCP8.5 (Antonioli et al. 2020). The physical destruction of such habitats, together with other drivers, such as air warming and droughts, may threaten the structure and function of salt marshes and trigger species shifts. In the North Adriatic Sea, the combined effects of inundation, increased temperature and decreased precipitation result in rapid species composition changes from perennial to annual (Strain et al. 2017). This should be regarded as an early warning sign of a deteriorating ecosystem (O’Leary *et al.* 2017). Additionally, the Mediterranean will potentially experience a sharp drop in the richness of *Spartina* spp. With higher potential for invader species of *Spartina* spp. (e.g., *S. anglica*) to expand northward (Borges *et al.* 2021).

Coastal aquifers

Risks here are projected to be high to very high starting from a ΔSST = + 0.8°C (medium confidence) (n = 7; Fig. 5). It is noteworthy that the same number of studies (n = 7) found moderate to high risk, but with low confidence level, which is why we assigned the first category to this ecosystem. The studies considered in this risk assessment (high to very high risk) clearly show that SLR is the main driver (Carneiro *et al.* 2010; Sefelnasr and Sherif 2014; Romanazzi et al. 2015; Al-Najjar *et al.* 2022; Schorpp et al. 2023) (Fig. 6). Other drivers include seawater intrusion (Romanazzi et al. 2015; Lyra and Loukas 2023; Schorpp et al. 2023), decrease in precipitations (García-Ruiz *et al.* 2011), and air warming (Stigter et al. 2014) (Fig. 5). The main projected risks include decreasing trends in groundwater levels, mostly in the recharge zone (Stigter et al. 2014) with growing effects of seawater intrusion (Romanazzi et al. 2015; Lyra and Loukas 2023; Schorpp et al. 2023), considerable changes in flow velocity, the drainage of the aquifer upstream areas (Carneiro *et al.* 2010), and losses in groundwater resources (Sefelnasr and Sherif 2014). In addition, the decrease in precipitations is expected to increase groundwater consumption, exacerbating the withdrawal trend (Al-Najjar *et al.* 2022). Other studies project moderate to high risks (n = 7), with a groundwater recharge decreasing trend as a response to changes in precipitation (El Asri et al. 2022). This variability in groundwater recharge posed by the high variability of precipitation will increase the aquifer's deterioration potential of both its quantity and quality status, and clearly stating that seawater intrusion might have stronger impacts compared to SLR (Pisinaras et al. 2021). Other studies (not included in this risk assessment as they do not present projections), project the submersion of large areas in the coastal zone (e.g., the Nile Delta) and a landward shift of coastline by several kilometers (Sherif et al., 2014), showing negative effects of saline conditions on survival and reproduction of soil invertebrate species (Owojori et al. 2008, 2014) or on avoidance behavior of earthworms (Bencherif et al. 2015).

IV. Conclusions

In order to determine the projected future risks in the Mediterranean Sea and its marine and coastal ecosystems, a systematic risk assessment exercise has been conducted relying on the available literature and based on the IPCC methodology. Our results reflect a diversity of responses of key habitats and ecosystems in the Mediterranean Sea, towards various climate change risks under multiple climate change scenarios. When ΔSST exceeds 0.8°C relative to 1976–2005 period, risks are projected to be high to very high (low to medium confidence) for seagrass meadows and seaweeds, and moderate to high for fish (when ΔSST exceeds 0.8°C). Epipelagic ecosystems are predicted to be more resilient as the projected risks vary from undetectable to moderate. For coralligenous habitats, moderate to high risks are projected when ΔSST exceeds 3.1°C (medium confidence). Moreover, our assessment evidences that all considered coastal ecosystems are expected to experience high to very high risks when ΔSST exceeds 0.8°C (medium to high confidence level), except for rocky coasts that are predicted to be more resilient as their risk transition is expected to vary from moderate to high (medium confidence).

Similar to the global ocean, all Mediterranean coastal ecosystems are projected to face higher risk levels than open marine ecosystems. The remarkably higher projected vulnerability of these ecosystems might be related to the rates of climate change in the Mediterranean that exceed global trends for most variables. However, climate change-related stressors seem to impact marine and coastal ecosystems differently than in the global ocean, as epipelagic and coralligenous ecosystems are expected to be more resilient while seagrass meadows and seaweed are predicted to have higher risks.

Our meta-analysis also shows a remarkable gap in the number of studies dedicated to project the future response of key ecosystems and biological groups, such as deep-sea habitats, megafaunal populations, seaweeds, and salt marshes. This clearly demonstrates the need to address gaps in modeling and projections' studies targeting these critical ecosystems to better understand their future behavior and efficiently take measures of protection and mitigation. Furthermore, our assessment demonstrates a significant geographical imbalance as most studies are Euro-centric, focusing predominantly on the Northern and Western Sub-basins of the Mediterranean Sea.

This study ultimately highlights the main risks projected for key open marine and coastal ecosystems in the short- and long-term, under various climate change scenarios, and can be used as a baseline to guide researchers on gaps and areas where the uncertainty is high and need to be urgently addressed, and policymakers on the ecosystems that need urgent measures to efficiently improve their resilience.

Declarations

Author Contribution

A.H. and M.J. conceptualized the study, with the methodology jointly developed and agreed upon by A.H., M.J., J.P.G., P.L., and W.C. A.H., M.J., and M.M. carried out the application of the methodology. The main text, figures, and tables were prepared by A.H., M.J., and M.M., and the key results were discussed collaboratively with all authors to enhance the interpretations. W.C. and A.H. prepared the reference list. All authors contributed to the review and finalization of the manuscript.

Data Availability

All data generated or analyzed during this study are included in this published article [and its supplementary information files].

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Footnotes

1. 0.13°C should be added to obtain the SST warming level with respect to preindustrial (see section S4)

Figures

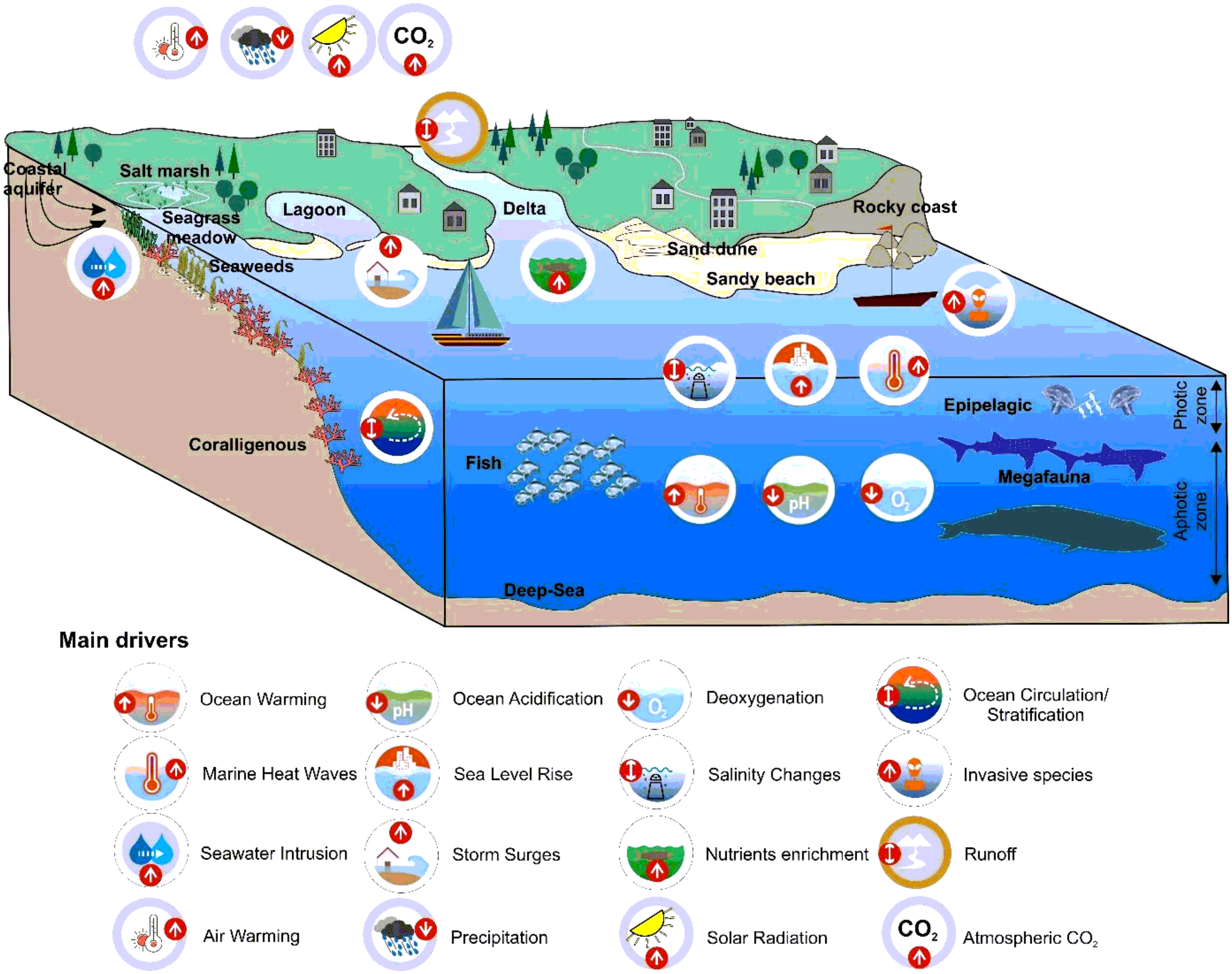

Figure 1

Schematic illustration of i) the different open marine and coastal ecosystems for which we assessed risk levels, and ii) the main drivers taken into consideration in this assessment.

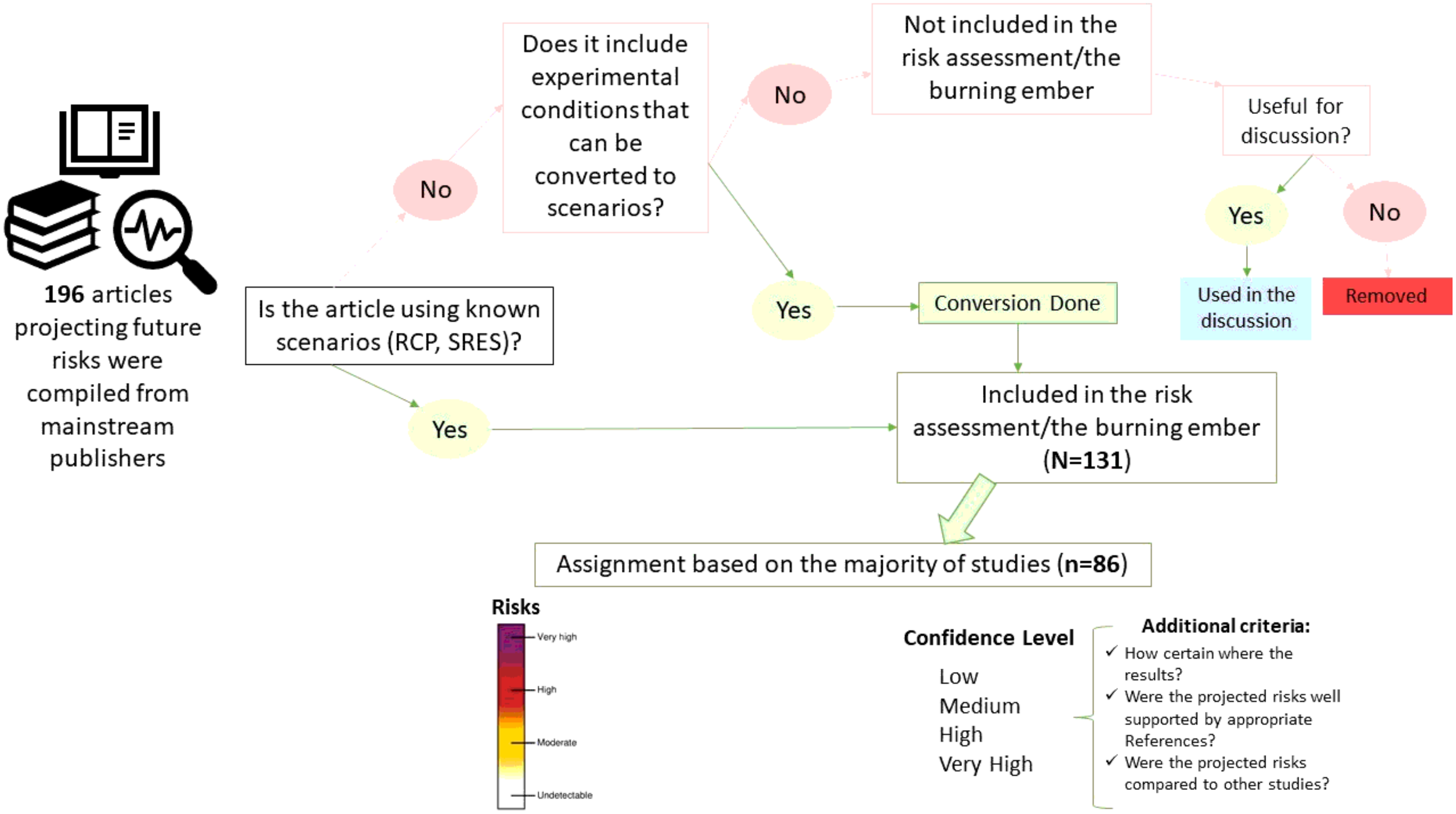

Figure 2

Work-flow diagram resuming the systematic approach used, from the literature assessment to the assignment of risks and confidence levels.

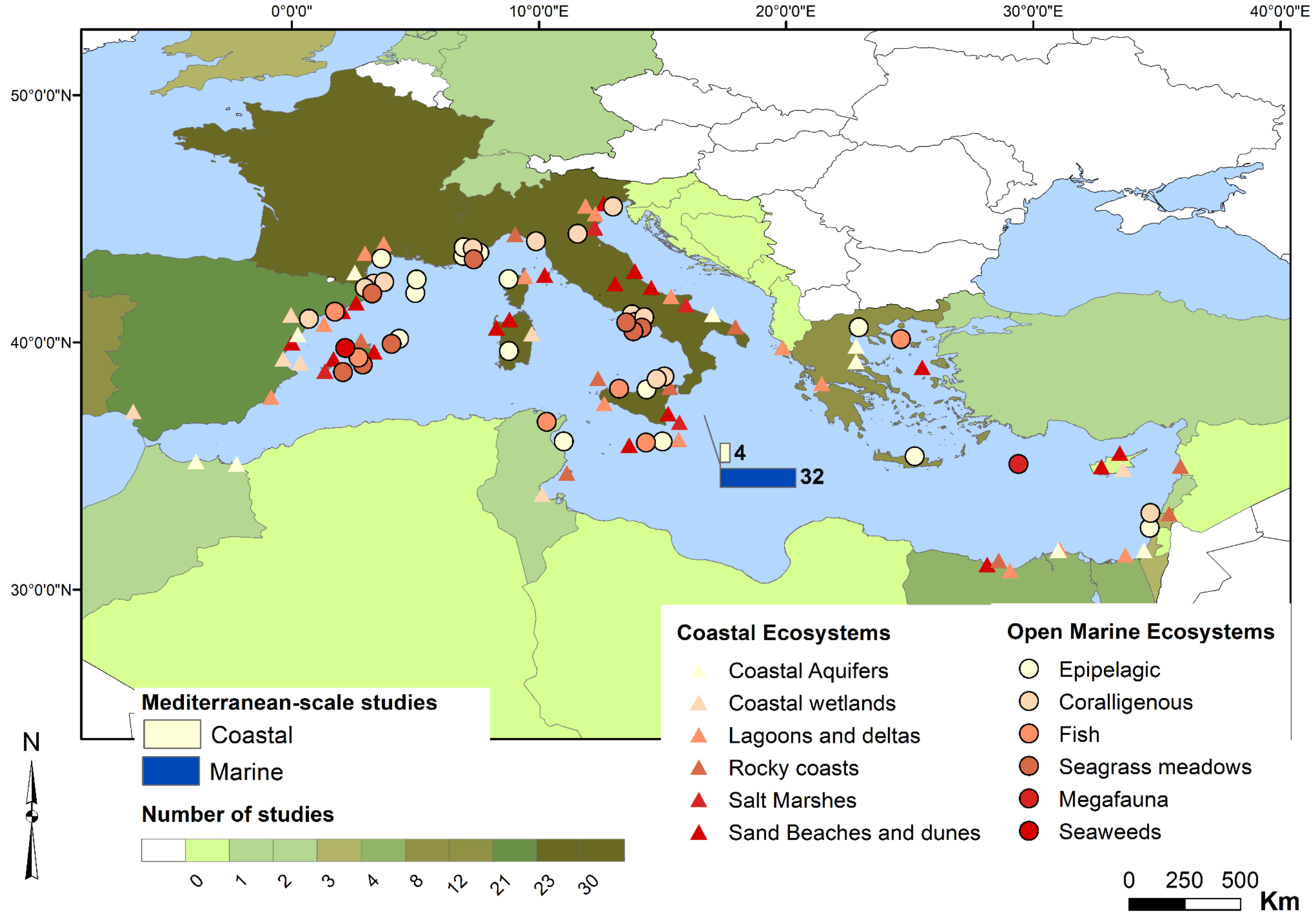

Figure 3

The geographic locations of the studies taken into consideration in the risk assessment (by country of the first author) and their study sites.

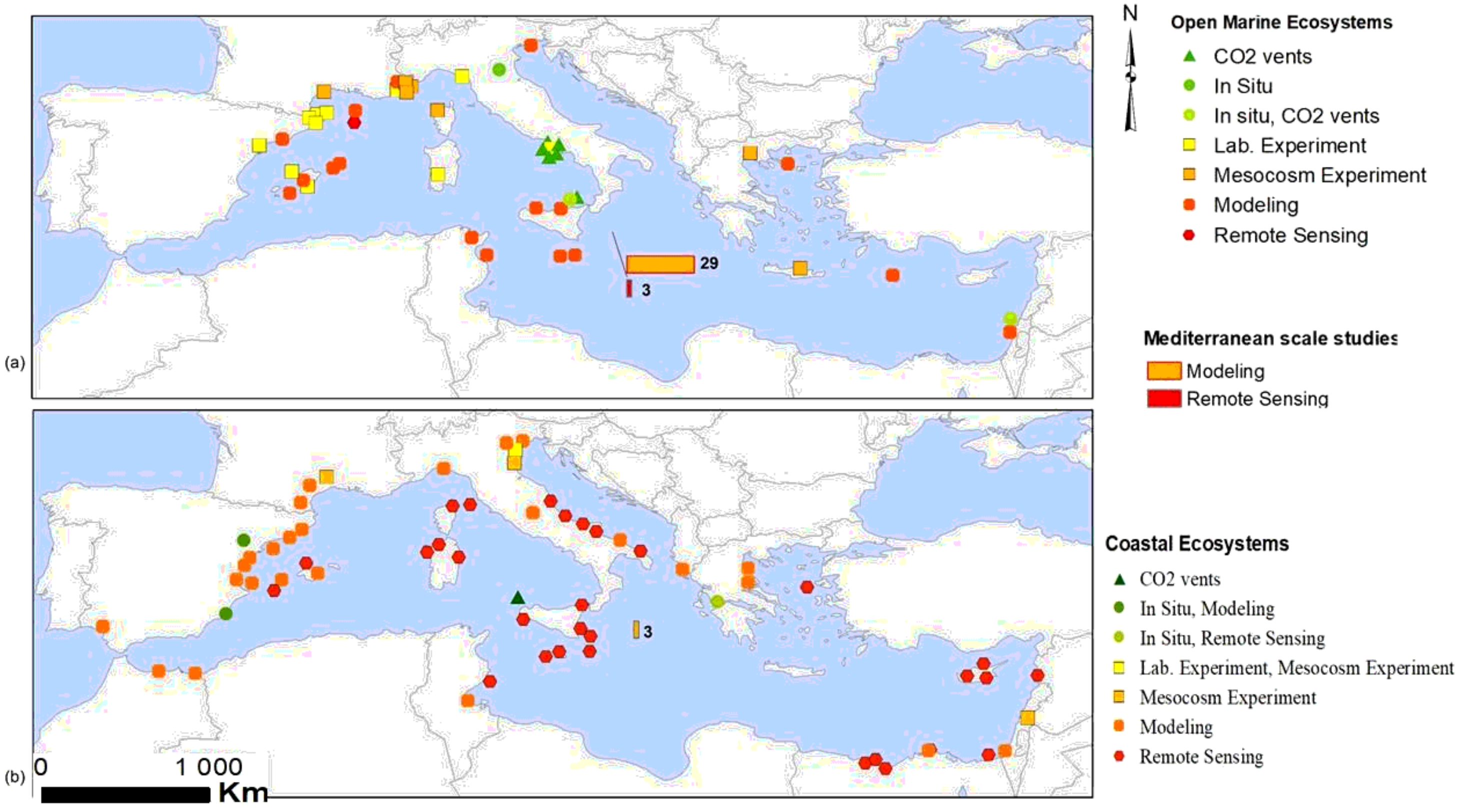

Figure 4

Types of the studies assessed in this paper.

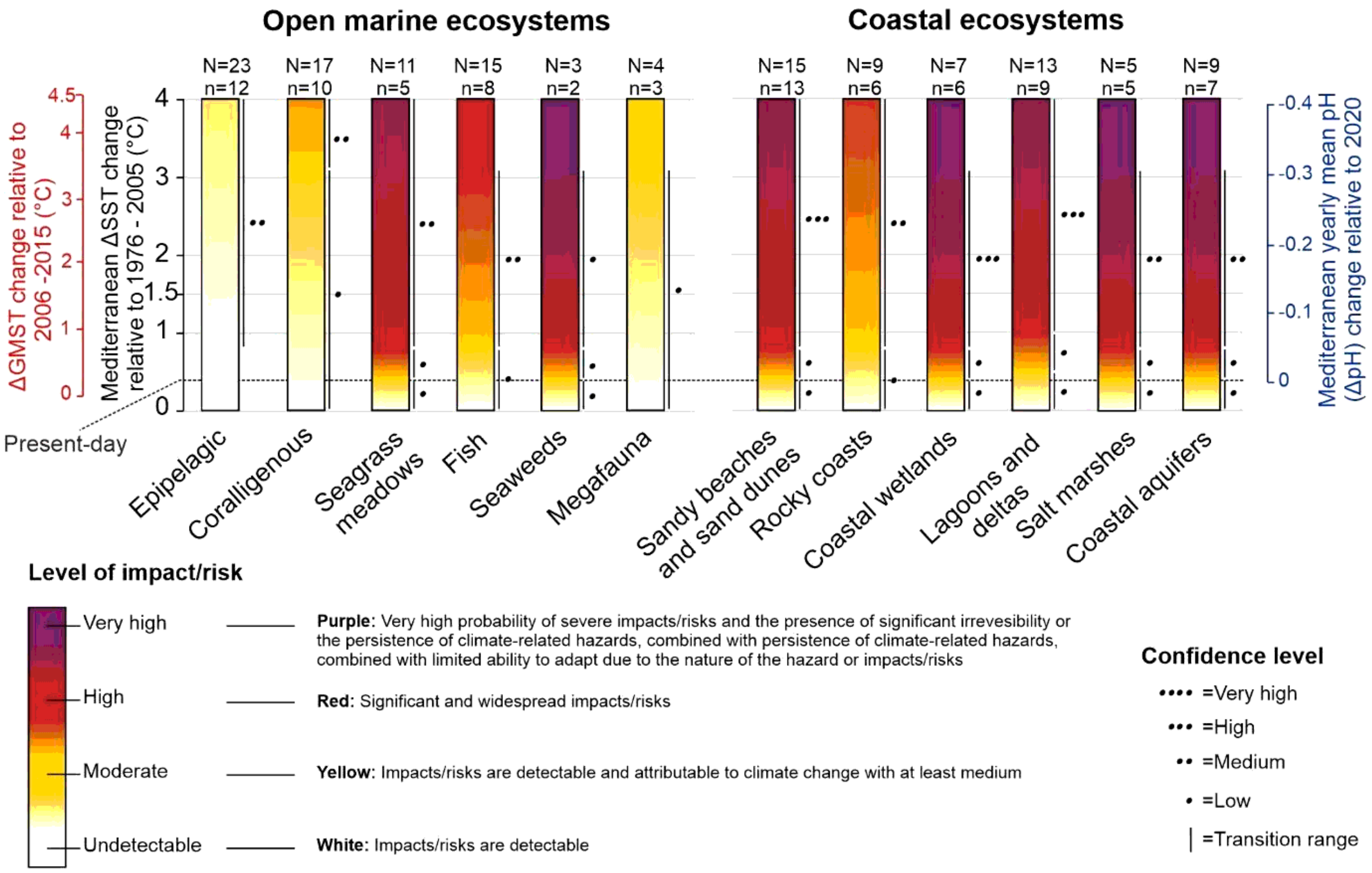

Figure 5

Risk assessment diagrams for open marine and coastal ecosystems in relation to observed and projected climate impacts on ecosystem structure, functioning and biodiversity. **N** is the total number of studies compiled, and **n** is the total number of studies taken into consideration in the bar. See Supplementary Materials S3 and S4 for details on the conversion of ΔGMST, Mediterranean ΔSST and ΔpH with respect to the reference and pre-industrial periods.

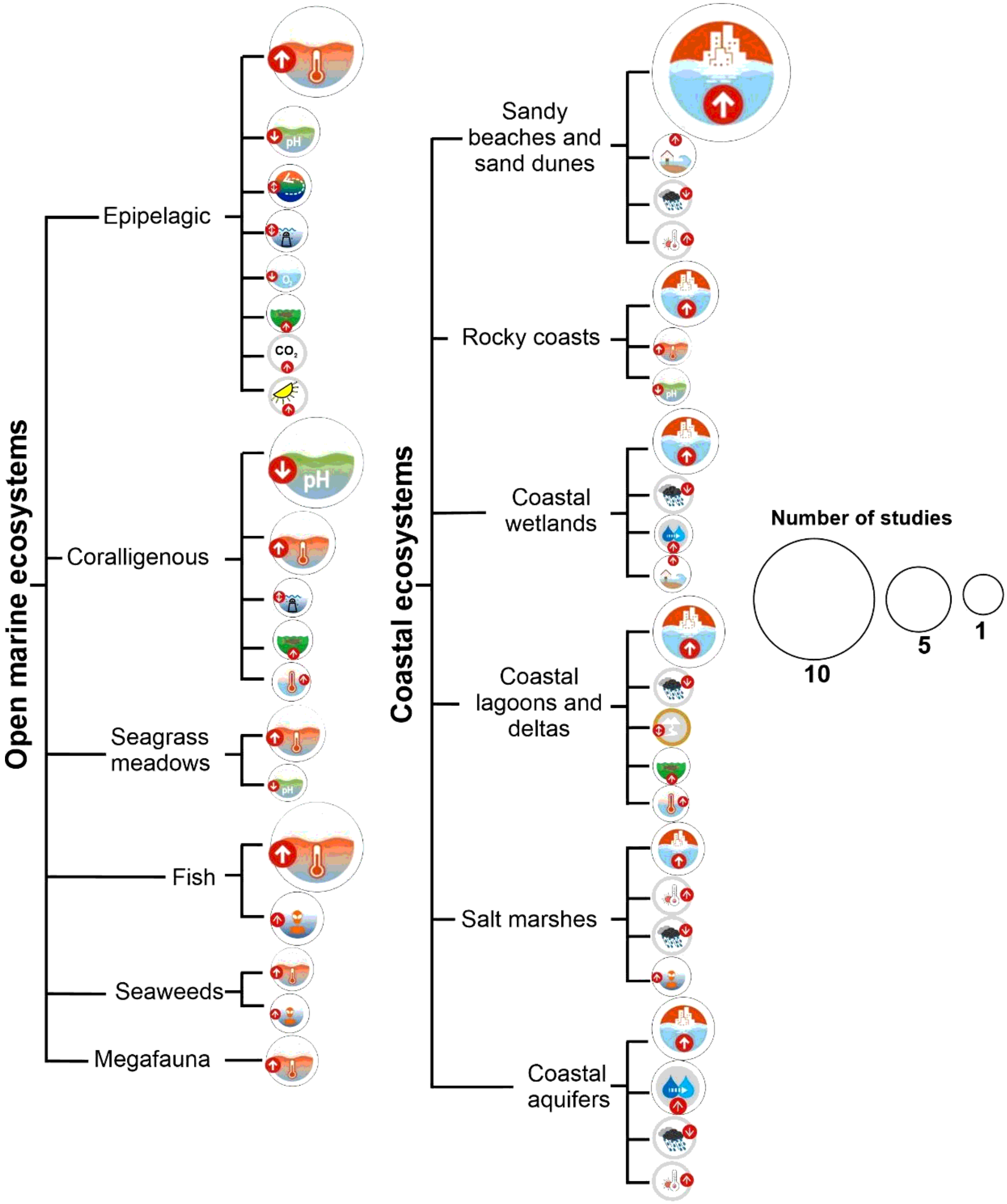

Figure 6

Schematic illustration of the main drivers assigned to the burning ember risk assessment for every habitat in marine and coastal ecosystems. The icons are the same as the ones used in Figure 1. The diameter of the circle indicates the number of studies pointing out a specific driver.

Supplementary Files