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Climate change risks on key open marine and coastal mediterranean ecosystems

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Mediterranean open marine and coastal ecosystems face multiple risks that impact their unique biodiversity, with climate change representing a major ongoing threat. While these ecosystems are also under pressure from non-climatic anthropogenic drivers (e.g., overfishing, pollution), this study primarily focuses on risks related to climate change. 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) are relatively more resilient compared to others, probably because of their long evolutionary history and the presence of a variety of climatic and hydrological conditions. However, high-emission scenarios in specific sub-basins, in addition to acidification impacts, could reduce this resilience, decreasing both habitat extent and ecosystem function dramatically. 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.

Keywords Climate change, Open marine ecosystems, Coastal ecosystems, Scenarios, Mediterranean sea, Risk assessment

The Mediterranean Sea is one of the most important regions in the world in terms of marine biodiversity and is home to more than 17,000 marine species, almost 18% of all known marine temperate and subtropical species[1]. Among these species, ~ 20–30% are endemic[2], making it one of the main marine biodiversity hotspots of the world. Many key resident and transient marine organisms such as fish, shellfish, and top predators (e.g., cetaceans, 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[3]. Socio-economic and political disparities in the region are large and they influence the future development and management of Mediterranean ecosystems[4,5].

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[6,7]. Due to its unique geological, climatic and hydrological features[1,8], the Mediterranean Sea is critically affected by climate change[9–12]. The projected

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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[13–15].

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[16]. 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;[17]). Warming will be particularly strong in summer, likely to exceed the global annual rates by 50%[18]. An accumulated warming of 1.3 °C has been estimated for the Mediterranean Sea surface temperature (SST) from 1982 to 2019[19], less in the Western than the Eastern Mediterranean Basin with an increase rate that varies between + 0.29 to + 0.44 °C decade^{-1}[20–22]. 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;[23]). 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[16]. 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[24]. Intermediate and deep-sea temperature and salinity (below 400 m) are also significantly increasing[25–27]. 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[28].

Marine heat waves are projected to become longer, more intense, and more frequent[21,29–32]. Although the intensity of precipitation extremes is projected to increase in some areas of the Northern Mediterranean[17,33,34], 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[16,18].

Warming enhances ocean thermal stratification[35], which may influence biogeochemical processes such as nutrient cycling and oxygen distribution. In stratified conditions, reduced vertical mixing can limit nutrient supply to surface waters and decrease oxygen replenishment at depth, potentially contributing to eutrophication and oxygen depletion in some areas. Additionally, increased dissolved organic carbon concentrations in the surface layer may play a role in these dynamics, although the mechanisms and regional expressions remain complex and context-dependent[36–38]. Increasing atmospheric CO_2 results in acidification of both surface and deep waters[5]. 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[5]. 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[5,39–41]. This pH decrease is ~ 1.5-fold more pronounced than the average global ocean (~ 0.3–0.4 units by the year 2100;[42]), according to most pessimistic scenarios[40,41]. Some Mediterranean sub-basins might experience more exacerbated acidification trends than the global ocean in the future[5,12,43].

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[1,44], and coastal erosion[45,46]. 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[47] and of 1.7 mm yr^{-1} since the mid-20th century[48], similar to the global trend, increasing to about 2.57 mm yr^{-1} since 1993 (based on satellite altimetry[49]), . Mediterranean sea level is projected to rise by 20 to 110 cm by the end of the 21st century compared to the 2000s[16]. Although sea level change can differ regionally due to ocean circulation and mass redistribution, projections suggest that these factors will largely balance out in the Mediterranean, leading to sea level rise rates similar to the global average[50].

Combined impacts of climate-related habitat changes and non-climatic stressors—such as pollution, overfishing, habitat degradation, and invasive species—pose unprecedented risks to Mediterranean Sea biodiversity and ecosystem resilience, potentially pushing many species beyond the environmental conditions necessary for acclimation or adaptation. Key open marine and coastal ecosystems are already impacted, threatening their diversity, as well as the services and resources they provide[51,52]. 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 focus on climatic drivers and present an integrated overview of the main related 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[1] to evaluate the responses of key populations and ecosystems, towards various climate change risks under multiple climate change scenarios by the end of the 21st century.

Methods

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;[3,53]. The coastal ecosystems here include sandy beaches and sand dunes, rocky coasts, coastal lagoons and deltas, salt marshes and coastal aquifers (Fig. 1). The group “open marine ecosystems” comprise epipelagic ecosystems, coralligenous ecosystems, seagrass meadows, fish populations, seaweeds and megafaunal populations (Fig. 1). For simplification and within these two groups (coastal and open marine ecosystems), the term ‘ecosystems’ refers to well-defined marine and coastal systems (e.g., epipelagic zone, coralligenous formations, seagrass meadows). ‘Habitats’ denote specific biophysical conditions within ecosystems. ‘Species’ are considered at the taxonomic level, whereas ‘populations’ refer to geographically or genetically distinct groups of species. Fish were assessed as a separate group due to their ecological and socio-

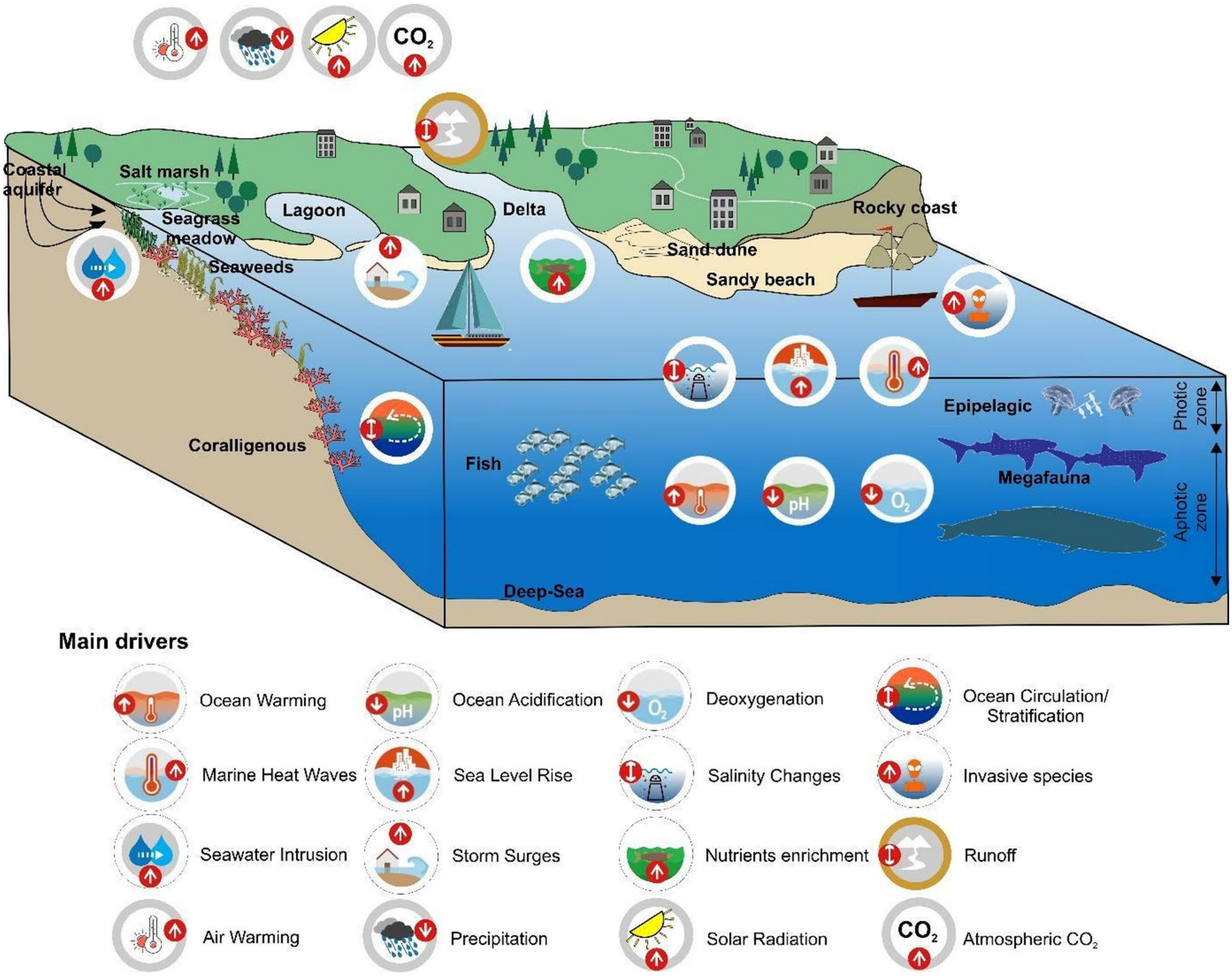

Fig. 1. Schematic illustration of (i) the different open marine and coastal ecosystems for which we assessed risk levels, and (ii) the main drivers taken into consideration in this assessment.

economic significance but are not considered ecosystems themselves. The detailed definition of each entity 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[54]. Throughout the paper, the following definitions are used: **Effects** refer to observed or projected changes in species, communities, or ecosystems due to climate-related stressors (e.g., shifts in species distribution, physiological responses). **Impacts** describe broader ecological or functional consequences resulting from these effects, including changes in ecosystem structure, function, and services. Whereas, **risk** is defined following the IPCC framework, as the result of the interaction between hazard (climate stressors), exposure (species/ecosystem presence in affected areas), and vulnerability (susceptibility and adaptive capacity).

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). More specifically, we prioritized studies that provided scenario-based projections of climate change impacts on Mediterranean ecosystems, excluding those focused solely on past or present observations. The selection process emphasized predictive assessments, including modeling, laboratory experiments, mesocosm studies, and controlled in situ research, as these were essential for constructing the burning embers risk assessment. To

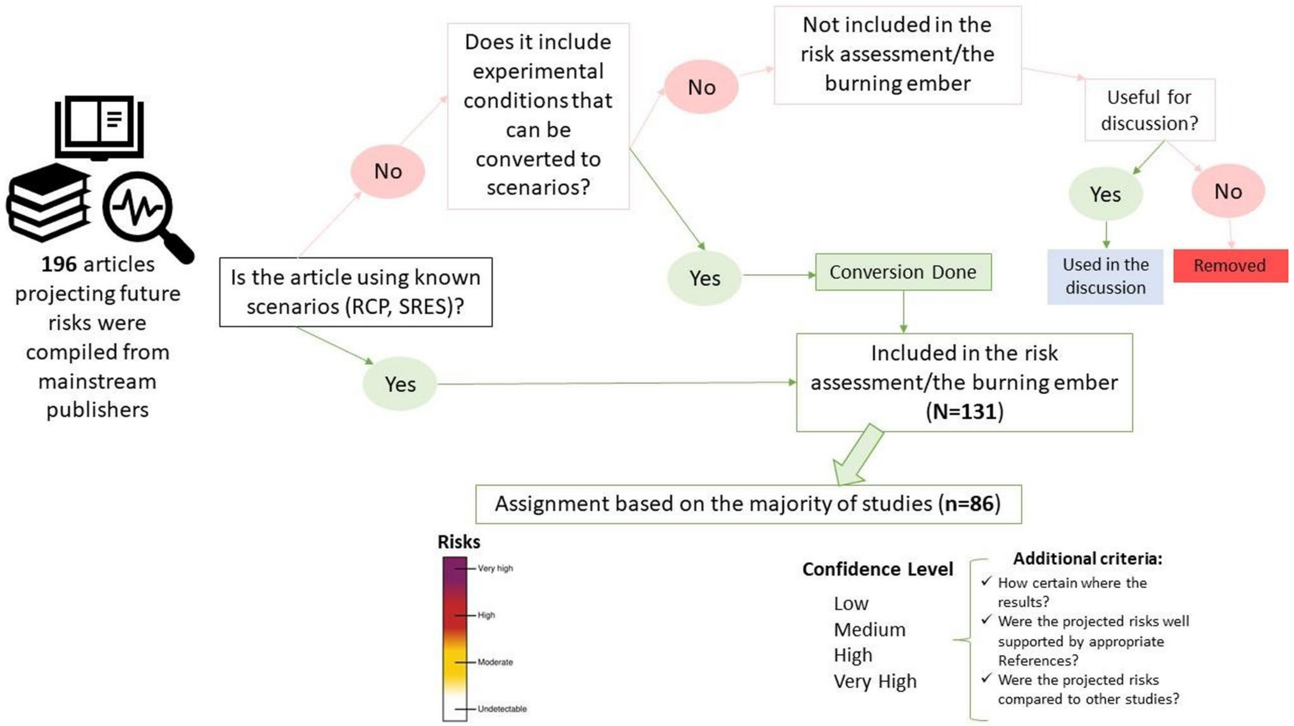

Fig. 2. Work-flow diagram resuming the systematic approach used, from the literature assessment to the assignment of risks and confidence levels. *Literature has been compiled from various sources, such as Google Scholar, Scopus and ResearchGate.*

ensure realism, we included studies that aligned with recognized climate scenarios (e.g., RCP, SSP) and IPCC methodologies, used regionally relevant temperature and pH projections, and incorporated cross-validation with in situ data. Geographic, temporal, and spatial disparities were addressed by assigning confidence levels based on study agreement and methodological robustness, with limitations explicitly discussed in the manuscript. The decision tree selection process (Fig. 2) follows a stepwise approach, prioritizing studies based on methodological robustness, emission scenario clarity, and geographic relevance. Further details on study selection criteria and confidence level assignment are provided in Supplementary Material S3.

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 studies tackling multiple 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 ecosystems are the epipelagic with 16 study sites and 11 regional studies, followed by fish populations (7 sites and 11 regional studies), and coralligenous ecosystems (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.

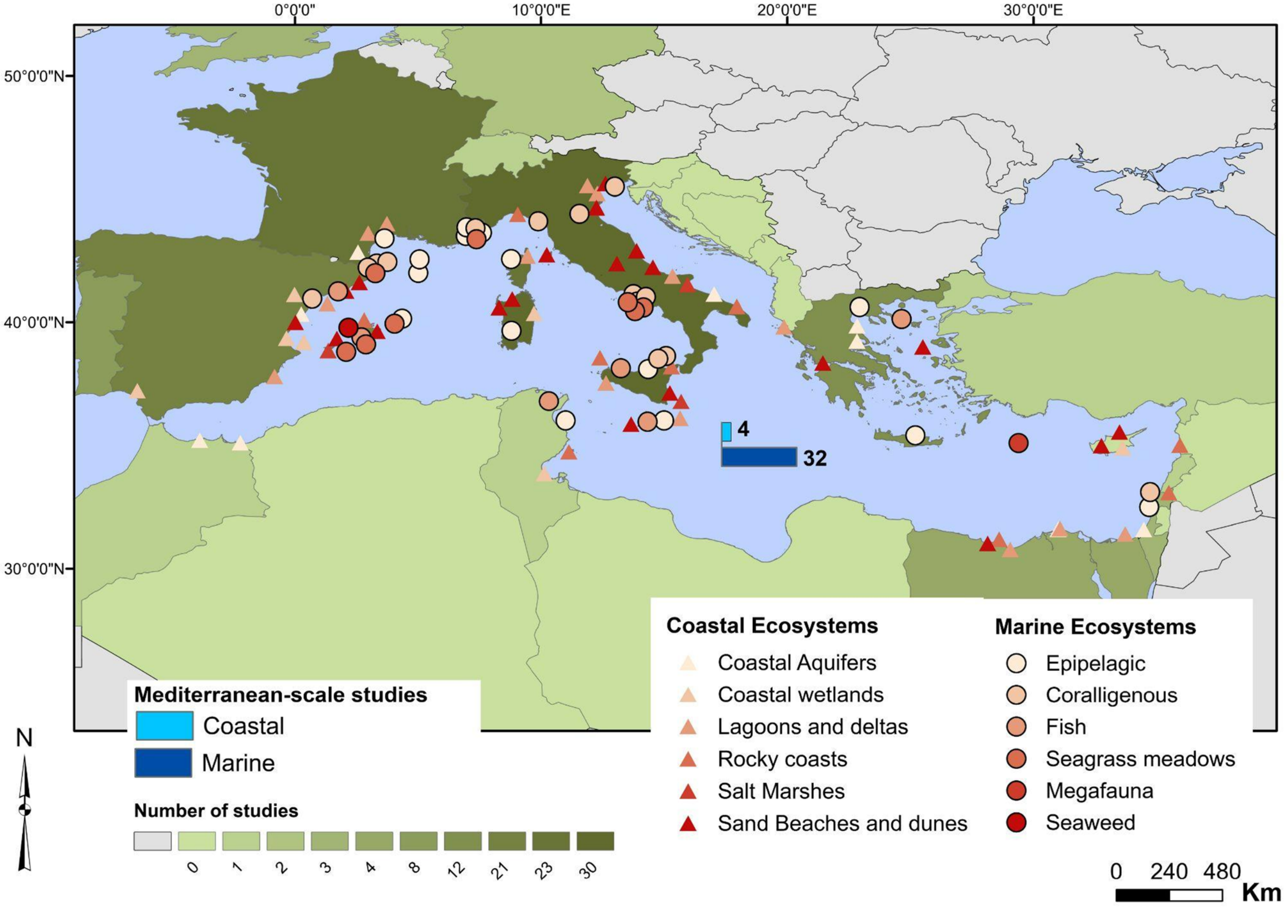

Fig. 3. The geographic locations of the studies taken into consideration in the risk assessment (by country of the first author) and their study sites.

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.

Results and discussion

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 1°C above the reference period 1976–2005 (0.13 °C should be added to obtain the SST warming level with respect to preindustrial [see section S4]), 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).

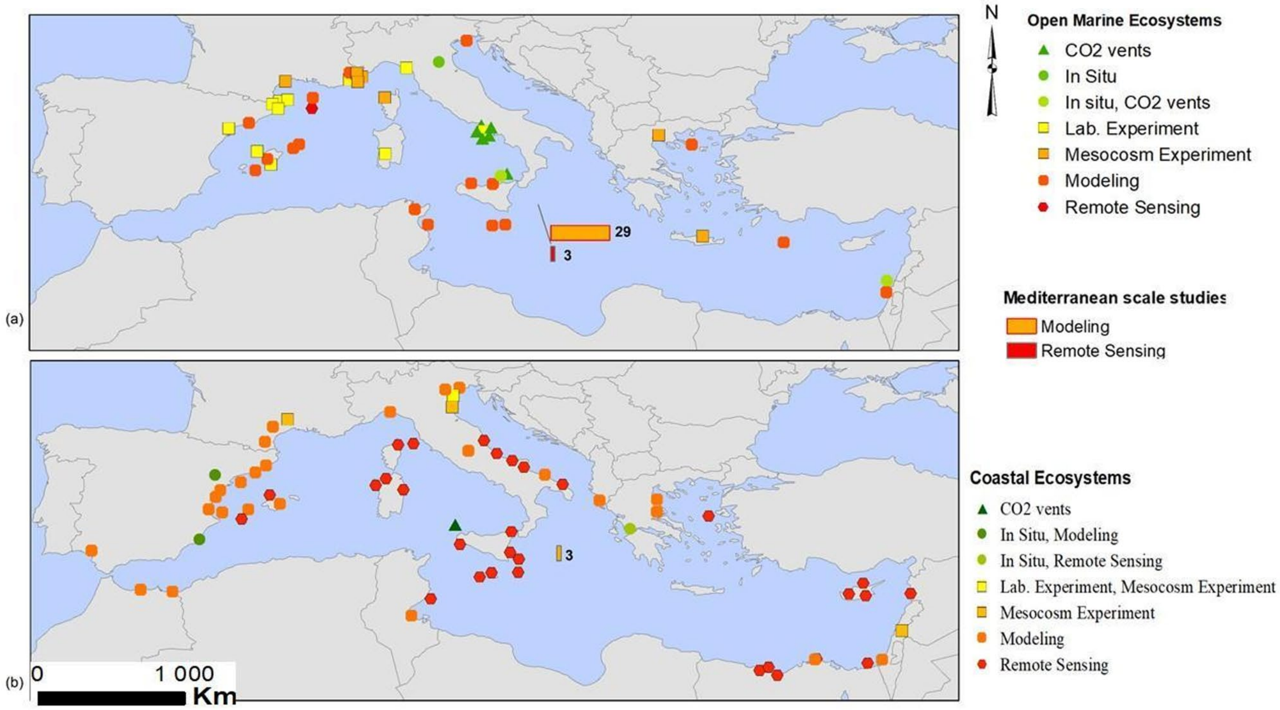

Fig. 4. Types of the studies assessed in this paper.

Open marine ecosystems:

Epipelagic: Most studies highlight ocean warming as the main driver[40,4155–60], with risks projected to be undetectable to moderate under $+0.8$ °C $<\Delta\mathrm{SST}<+6$ °C (medium confidence) ($n=12$; Fig. 5). Ocean acidification is the second most relevant driver[40,58,61] (Fig. 5). Other less significant drivers include changes in ocean stratification/circulation[62,63], changes in salinity[59,64], nutrient enrichment[40], deoxygenation[40], atmospheric CO_2/acidification[41], and solar radiation[60] (Fig. 6).

Ocean warming is expected to impact 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[56–58,62,65–67], particularly pico- and nanophytoplankton, and bacteria[62]. However, several studies also highlight that the abundance of relatively large phytoplankton species (e.g., *Cyclotella* sp. and *Thalassiosira* sp.) is expected to decline due to warming, with an undetectable to moderate risk, potentially decreasing the export and energy transfer to higher trophic levels, with a very limited impact from ocean acidification/increasing $p\mathrm{CO}_2$[56–58,61,67]. 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[65,66,68–71]. Changes in species richness are also projected due to increasing temperature (predominantly during marine heat waves[72]; and changes in ocean stratification/circulation[63,73]. 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; [74]), weakened winter convection, surface layer warming and the changing variability of extreme meteorological events[62,75].

In combination, these changes are expected to modify the seasonal blooms, as spring blooms may occur earlier[62,76] and last longer[77]. 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[78–80]. Epipelagic harvested species (e.g., fish, macroinvertebrate, cephalopods) are projected to significantly change in terms of stocks and distribution, mainly due to ocean warming[60,65,67,81]. Although our analysis focuses specifically on climate-related projections, it is important to acknowledge that the ecological responses of Mediterranean marine species—particularly harvested groups such as fish and invertebrates—are also shaped by long-standing non-climatic pressures, notably overfishing. Numerous studies have documented the persistent overexploitation of fish stocks across the region and its role in altering species composition, biomass, and ecosystem functioning (e.g[14,82,83]). While disentangling these effects lies outside the scope of this climate-focused synthesis, the interaction between climatic and anthropogenic drivers likely influences the magnitude and direction of projected biological changes. This reinforces the need for integrated management approaches that account for multiple, co-occurring stressors. Overall, these various contradictory findings reflect the specificities of sub-regions and drivers taken into consideration. Mediterranean basins and sub-basins will likely face non-uniform future risks, i.e., on primary production and species diversity[40,41,59,66,84].

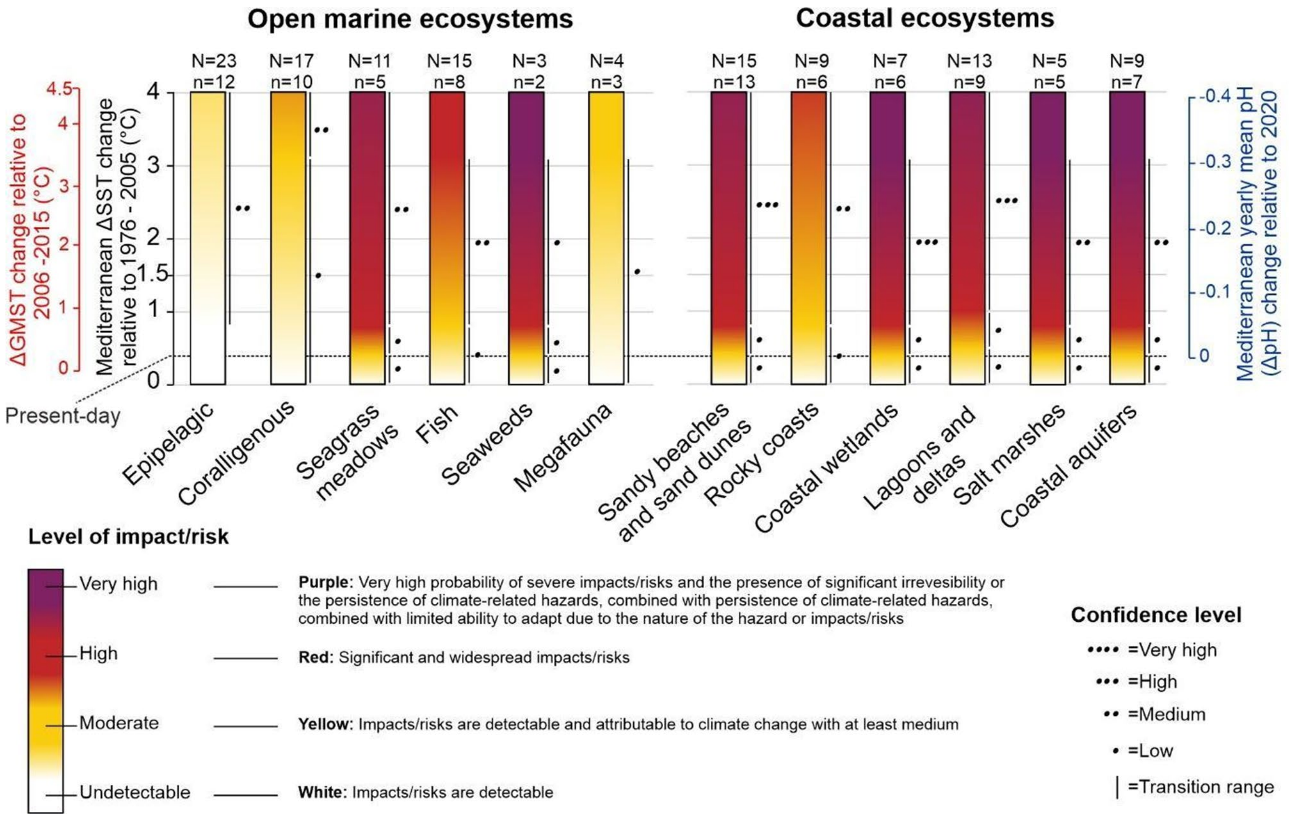

Fig. 5. Risk assessment diagrams for open marine and coastal ecosystems in relation to observed and projected climate impacts on ecosystem structure, functioning and biodiversity. **N** is the total number of studies compiled, and **n** is the total number of studies taken into consideration in the bar. See Supplementary Materials S3 and S4 for details on the conversion of anomalies of the global mean surface temperature (ΔGMST), Mediterranean mean sea surface temperature (ΔSST) and Mediterranean pH (ΔpH) with respect to the reference and pre-industrial periods.

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[85–93], followed by warming[86,90–93] (Fig. 6). Other drivers were also mentioned, such as changes in salinity[93], nutrient enrichment[93], and marine heat waves[94] (Fig. 6). Most coralligenous species are expected to undergo physiological or ecological changes in response to ocean warming, but current studies suggest that these changes are unlikely to lead to their complete disappearance, contrary to earlier projections[5]. At projected warming levels above + 3.1 °C, some studies suggest that ocean acidification may impact early life stages of corals such as *Astroides calycularis*[95], while experimental and in situ studies indicate that combined effects of warming and acidification could alter rocky shore communities by reducing the presence of calcifiers such as scleractinian corals, sea urchins, and coralline algae[85]. 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[87,89]. The Mediterranean red coral *Corallium rubrum*'s skeletal growth and spicule morphology could be detrimentally affected by low pH[88]. Multiple studies suggest that ocean warming and acidification may act synergistically to affect calcifying organisms in the Mediterranean. For example, warming can increase the metabolic demands of Mediterranean scleractinian corals, and when combined with lower pH, may impair cellular functions, potentially leading to mortality rates of up to 60%[91]. Similarly, for coralline algae such as *Lithophyllum cabiochae*, projections indicate that under combined warming and acidification, net dissolution may exceed calcification, increasing the risk of mortality[86]. While the physiological tolerance of some coral species to acidification has been documented[95], calcifying algae living near their upper thermal limits are especially vulnerable and may no longer contribute effectively to reef accretion under future conditions[90]. Other studies reveal that risk levels for coralligenous reefs can be significantly higher under combined stressors and in specific sub-basin contexts, warranting a more cautious interpretation of regional projections. For example, under severe RCP 8.5 forcing, the Northern Adriatic may experience major contractions in coralligenous habitat[93]. This same study also showed that 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 ecosystems, potentially leading to biodiversity loss in certain regions, such as in the Northern Adriatic Sea[93]. Additionally[96–98], demonstrated consistent patterns of reduced calcification, acidification-driven algae shifts, and cascading losses in ecosystem structure

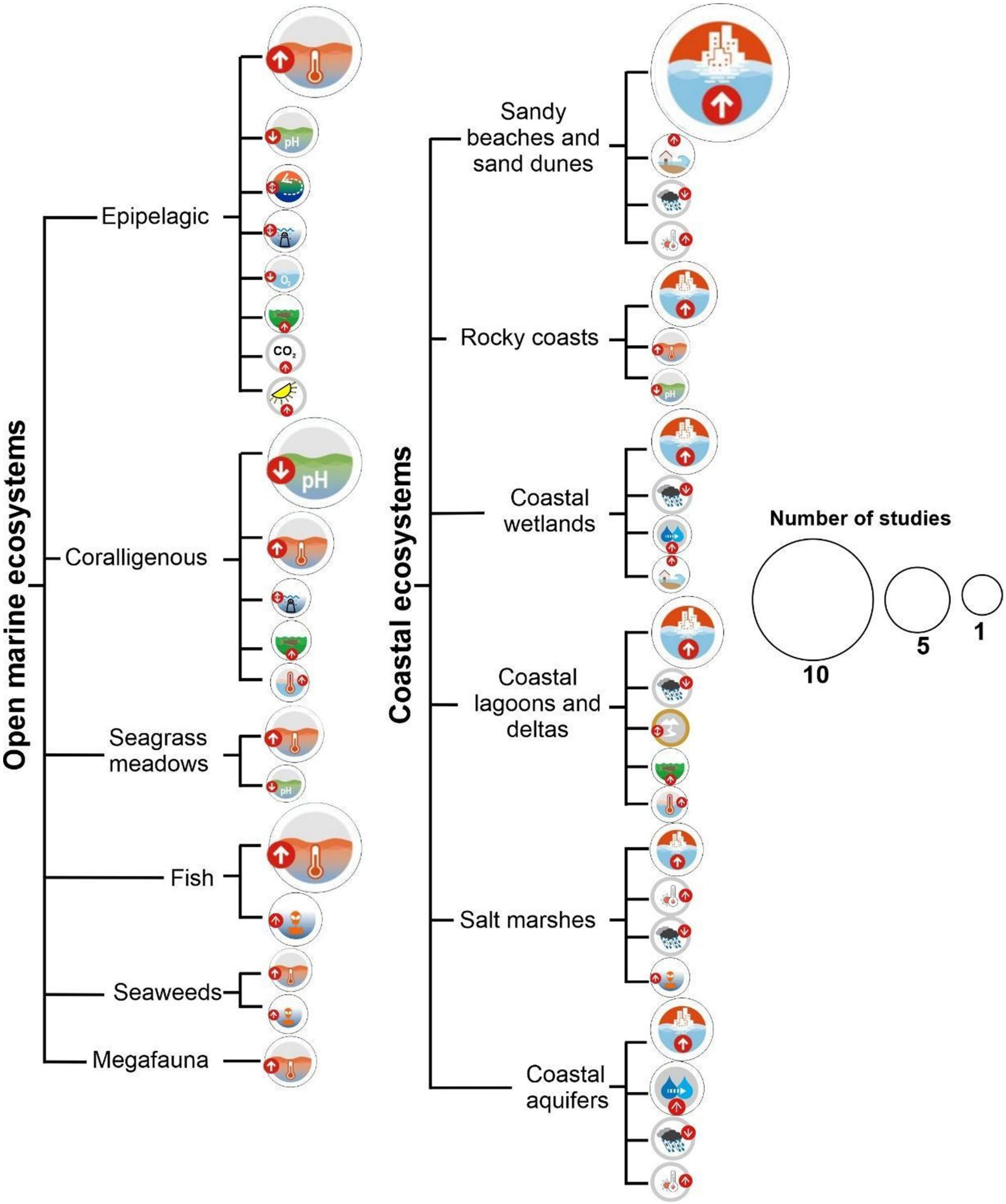

Fig. 6. Schematic illustration of the main drivers assigned to the burning ember risk assessment for every habitat in marine and coastal ecosystems. The icons are the same as the ones used in Fig. 1. The diameter of the circle indicates the number of studies pointing out a specific driver.

and services. These layered findings suggest that climate-driven stressors—particularly in acidified, nutrient-affected, or sub-basin-vulnerable areas—could elevate risks for coralligenous reefs beyond the mean projections.

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[99] or mineralogical[100] 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[89]. Under low pH conditions, some species of crustose coralline algae become more resistant while others are becoming more sensitive[101]. *Ellisolandia elongata* may withstand projected temperature changes[102,103], 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[104]. Coverage of invertebrate calcifiers and crustose coralline algae appears not to be affected by the lowered pH[105].

Although coralligenous species have a long evolutionary history in the Mediterranean, which may contribute to some degree of resilience, their persistence is contingent on environmental conditions remaining within their tolerance limits. Rising sea temperatures and increasing marine heatwave frequency are expected to drive species beyond these thresholds, placing them at high risk. Evidence from other oceanic areas shows that calcifying corals and reef habitats are already experiencing mass bleaching and mortality due to thermal stress, compounded by local stressors such as pollution and overfishing. Mediterranean corals might face similar escalating risks, underscoring the urgency of conservation efforts. The literature reveals considerable variability in species' responses to climate-related stressors within this ecosystem, with some taxa showing tolerance or adaptability, while others exhibit signs of stress or decline[94]. This heterogeneity underscores the potential for shifts in community structure under future climate conditions.

Seagrass meadows: Risks are projected to be high to very high with $\Delta SST = +0.8$ °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[106]. Ocean acidification contributes to changes in benthic communities, altering competitive dynamics between calcareous and fleshy seaweeds[107]. 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[105], *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[108], specifically in the Eastern Mediterranean[109]. Other studies are projecting functional extinction of *P. oceanica* by mid-century, even under relatively mild GHGs emissions[110]. Seagrass shoot mortality rates and losses are projected to increase with rising temperatures[111], and younger life stages (i.e., seedlings of *P. oceanica*) may be particularly vulnerable[1].

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[110]. These results have been confirmed in a recent study[112], 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*[113]. 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[114]. 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[115] and the possible benefits from increased pCO_2[116]. Otherwise, more suitable habitats could become available for both tropical species, *Halophila stipulacea* and *H. decipiens*, during this century under all RCP scenarios[117]. The predicted rapid expansion of these non-native species could alter the Mediterranean's seagrass community and may have significant socio-economic consequences. Therefore, in addition to climate-driven stressors such as warming and ocean acidification, seagrass meadows are also significantly impacted by local environmental pressures, including nutrient enrichment, turbidity, habitat destruction from coastal development, dredging, and pollution from urban and agricultural runoff, all of which can exacerbate their decline.

Fish: Risks here 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 ($n = 8$; Fig. 5). Most of the projection-based studies included in our assessment identify ocean warming as the primary climate-related driver of change in fish populations[65,118–124], followed by invasive species[118,124,125] (Fig. 6). However, other anthropogenic pressures, most notably overfishing and habitat degradation, also exert significant and compounding effects, particularly through the disruption of key fish habitats such as spawning grounds[126]. These pressures, though beyond the direct scope of this climate-focused synthesis, play a critical role in shaping fish population dynamics in the Mediterranean and should be recognized as essential co-drivers in comprehensive, integrated risk assessments. These studies are mainly predicting a significant fish stock reduction (~ 30% for RCP4.5 and ~ 40% for RCP8.5;[123]) together with a contraction of the distributional range of commercial species, with a general biogeographical displacement towards North European coasts[120]. 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[121]. 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[118]. For example, suitable conditions for the lionfish, *Pterois miles*, are likely to expand to the Northern and colder areas even under mild warming scenarios[124]. Ocean warming may weaken deep overturning circulation, increasing water column stratification and reducing nutrient flux to surface waters. This is projected to lower primary production, with potential additive impacts on sardines due to food scarcity and synergistic effects on anchovy and mackerel, whose responses also depend on thermal tolerance and reproductive timing[123]. More severe risks are projected by other studies ($n = 3$), predicting a significant loss of climatically suitable habitats for endemic species[127] with climate-related local extinctions of the most harvested small pelagic species in Europe, mainly in the South-Eastern Mediterranean[81], and a considerable expansion of *Pterois miles* towards new areas[125]. 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[60,65,121,128] in parallel with potential distribution shifts northward (e.g., round sardinella;[128]).

Seaweeds: Risks here are projected to be undetectable to high below $\Delta SST = +0.8$ °C (low confidence) and high to very high (low confidence) above $\Delta SST = +0.8$ °C ($n=2$; Fig. 5). These studies identify ocean warming[129,130], followed by invasive species[129] 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[130]. This loss could have cascading effects on the whole ecosystem and its services[131,132]. 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[111] and gorgonians[133]. This process can be attributed to the reduction in biotic resistance of native communities to the arrival of non-indigenous seaweeds[129]. 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*;[103]). These results suggest marked differences in warming sensitivity within and between benthic communities[134].

Megafauna: Risks are projected to be undetectable to moderate below $\Delta SST = +3.1$ °C (low confidence) ($n=3$; Fig. 5). These studies are overwhelmingly stating ocean warming as the main driver[135–137] (Fig. 6). The main risks include a disproportionate loss of functional diversity[137], an increase in the daily energy expenditure and thus an alteration of the physiological functions of marine turtles[135] with contractions of their foraging space[136]. 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[136]. Although ocean warming is identified as the primary climate-driven risk to megafauna, these impacts are largely indirect, occurring through habitat modification, shifts in prey distribution and abundance, and altered environmental cues affecting migratory species (e.g., cetaceans and turtles). The scarcity of studies on Mediterranean megafauna, particularly for cetaceans, limits our understanding of climate-related effects, which are often confounded by other stressors such as pollution, overfishing, vessel strikes, and habitat degradation. These non-climatic factors may exert a stronger or more immediate influence on population dynamics and species distributions, highlighting the need for integrative assessments of cumulative risks. Overall, megafauna-related projections are very limited in the Mediterranean, highlighting a notable research gap and emphasizing the need for further studies on how climate-driven changes may affect their distribution and ecological roles (e.g. for sharks and other megafaunal species). Already observed changes include a poleward shift and an alteration of the migration timing for some cetaceans[138]. While expected risks encompass megafaunal range shifts for some species, such as the westward expansion of loggerhead turtles within the Mediterranean[139], others face the risk of local population collapse, as is the case of the critically endangered common dolphins *Delphinus delphis* in the Gulf of Corinth[140]. 21–31% of Mediterranean marine ecoregion species have high climate risk[11], 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[141], primarily deep-diving cetaceans such as sperm whales and Cuvier's beaked whales that inhabit the deep waters off southwestern Greece, are surrounded by much shallower seas that make it difficult to leave[142]. In addition, Mediterranean-wide shifts in prey distribution and abundance driven by climate change and anthropogenic disturbance are expected for the black anglerfish[143], which we include here due to its ecological role as a large benthic predator frequently assessed in climate-related deep-sea ecosystem studies—although it does not fit traditional definitions of marine megafauna.

Coastal ecosystems

Sandy beaches and sand dunes: Risks are projected to be undetectable to high below $\Delta SST = +0.8$ °C (low confidence) and high to very high (high confidence) above $\Delta SST = +0.8$ °C (Fig. 5). SLR is by far the dominant driver (Fig. 6)[144–155]. Other drivers include storm surges[146,155], changing precipitation and warming[156] (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[144,145,147]149–[152,154,155]. Due to their low elevation and proximity to the sea, sandy beaches are at higher risk[146,153,157,158] compared to dunes[147]. 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[159]. 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[148]. 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[159].

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). Among climate-related stressors, SLR is identified as the major driver (Fig. 6)[149,152160–162], with additional risks from ocean warming[161] and ocean acidification[163] (Fig. 6).

Compared to other coastal ecosystems, SLR-related risks appear lower for rocky shores at ΔSST above + 0.8 °C, primarily because their elevation provides some degree of protection[149,152]. However, localized impacts may be significant. For instance, certain rocky shore habitats in North-Eastern Sicily are projected to experience gravity collapse events due to SLR[162]. These physical changes will directly affect resident populations and biodiversity, as submerged horizontal rocky surfaces tend to host lower species richness compared to intertidal reef platforms[160].

In intertidal rocky shore communities, biodiversity shifts are expected. When permanently submerged, these communities may transition into either a structurally different but still rich assemblage (when protected from grazing) or a much poorer turf-dominated community (when exposed to grazers), leading to a drastic reduction in reef community net production[160]. Additionally, insects inhabiting splash pools, such as the culicid *Acartomyia mariae*, are vulnerable to both SLR and warming due to their strong dependence on temperature and salinity[161]. While *A. mariae* itself is not known to pose direct sanitary risks, changes in splash pool habitats could indirectly influence the distribution and emergence of other mosquito species relevant to human health, with implications for coastal ecosystem management.

Ocean acidification will also contribute to the degradation of specific rocky shore habitats, particularly vermetid reefs. The recruitment of these reefs, especially of pH-sensitive gastropods, is expected to decline[163]. Without reductions in CO_2 emissions and active conservation efforts, these reefs face a high risk of extinction. Similarly, patellids are projected to undergo significant range shifts by 2050 and 2100, with southern populations declining and northern populations expanding[164].

Overall, the impacts on rocky shores are highly habitat-dependent, with SLR driving physical changes, ocean warming influencing species distributions and community structure, and acidification threatening key ecosystem engineers like vermetid gastropods. These risks, coupled with seasonal and successional dynamics, emphasize the need for targeted conservation strategies for different rocky shore habitats.

Coastal wetlands: Risks to coastal wetlands are projected to be high to very high above $\Delta SST = +0.8$ °C (high confidence) ($n = 6$; Fig. 5). These risks are primarily driven by sea level rise (SLR)[146,149,165–167] (Fig. 6), with additional contributions from changing precipitation patterns[168,169], seawater intrusion[166], and storm surges[146] (Fig. 6). In this assessment, coastal wetlands refer specifically to intertidal and supratidal wetlands, including coastal freshwater and brackish wetlands, while excluding coastal lagoons, deltas, salt marshes, and coastal aquifers, which are analyzed separately. These wetlands are highly dynamic and sensitive to climate-induced hydrological shifts, with SLR and salinity intrusion expected to significantly alter wetland structure, water balance, and habitat stability.

Projected increases in salinity and sulfide concentrations may induce physiological stress in wetland biota, leading to community shifts and disruptions in ecosystem function[170]. In particular, altered hydrological conditions can impact crustacean and zooplankton communities hatching from resting egg banks, reducing the establishment of large branchiopods and copepods. This could shift wetland ecosystems from a zooplankton-rich clear-water state to a zooplankton-poor turbid state, fundamentally altering invertebrate diversity and food web dynamics[171].

Beyond direct habitat degradation, cascading ecological consequences are projected for wetland-dependent species. Waterbird populations that rely on these wetlands for breeding and residency may experience habitat loss and declining environmental suitability[168]. However, some migratory and wintering species, particularly small wading birds, may benefit from habitat shifts, as muddy areas and open water expand under increased salinity, enhancing foraging conditions[168].

Overall, climate-driven hydrological shifts, salinity changes, and extreme weather events are expected to fundamentally reshape coastal wetland structure and function, with significant implications for biodiversity, habitat stability, and ecosystem resilience. Without targeted conservation and adaptation efforts, these habitats will face increasing degradation and loss in the coming decades.

Coastal lagoons and deltas: Risks here are projected to be high to very high starting from a $\Delta SST = +1.0$ °C (high confidence) ($n = 9$; Fig. 5). SLR is by far the major driver affecting these ecosystems[149,153,172–174] (Fig. 5). Other drivers include changing precipitation[175], terrestrial runoff[175], nutrient enrichment[176], and marine heat waves[72] (Fig. 6). The predicted impacts include a remarkable increase of SLR (e.g., up to 160% in 2100 in the Northern Adriatic;[174]), causing floodings[173] and loss of important habitats nesting beaches, i.e., for the loggerhead (*Caretta caretta*), such as in the Egyptian coasts/Nile delta region[172]. These effects are expected to have significant environmental and socioeconomic consequences, as many lagoons and deltas will be highly vulnerable[153]. 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[175]. 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[72]. 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[176]. Otherwise, high to very high risks with low confidence level include more coastal hazards, causing significant loss of coastal lands[149] and continuous shoreline erosion[177]. Undetectable to moderate risks attributed to SLR are also expected in specific areas such as the Ebro Delta[178] with relatively higher rates in the Eastern Mediterranean Sea (e.g., Egypt) compared to its Western part[157]. Moderate risks are forecasted for macroinvertebrates in coastal lagoons due to ocean acidification[179]. 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[180]. Other studies (not included in our analysis as they do not present projections) show site-specific impact combinations[181]. In addition to the increasing vulnerability of coastal areas due to SLR[182], shifts in freshwater and nutrient runoff are projected to drive phytoplankton communities toward more extreme "famine or feast" dynamics—characterized by sudden blooms followed by periods of scarcity—altering ecosystem functioning in shallow coastal lagoons[183]. Human activities are expected to worsen the risks due to natural habitat destruction and alteration of the hydrological cycle (e.g[184]).

Salt marshes: Risks are projected to be high to very high above $\Delta SST = +0.8$ °C (medium confidence) ($n = 5$; Fig. 5), with SLR as the main driver[149,185] (Fig. 5). Other drivers also include atmospheric warming, precipitation change[186], and invasive species[187] (Fig. 6). The risk of SLR was mostly assessed along the Italian coasts (Sicily and coastal areas of the Adriatic Sea;[149,150,185]). 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[150,185]. 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[149]. The physical destruction of such habitats, together with climate-related drivers such as air warming and droughts, is already altering the structure and function of Mediterranean salt marshes. In the North Adriatic Sea, for instance, the combined effects of inundation, rising temperatures, and reduced precipitation are leading to rapid vegetation shifts from perennial grasses to annual succulents[186] - a potential early warning sign of ecosystem deterioration[188]. 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[187].

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[189–193] (Fig. 6). Other drivers include seawater intrusion[191,193,194], decrease in precipitations[195], and air warming[196] (Fig. 5). The main projected risks include decreasing trends in groundwater levels, mostly in the recharge zone[196] with growing effects of seawater intrusion[191,193,194], considerable changes in flow velocity, the drainage of the aquifer upstream areas[189], and losses in groundwater resources[190]. In addition, the decrease in precipitations is expected to increase groundwater consumption, exacerbating the withdrawal trend[192]. Other studies project moderate to high risks ($n = 7$), with a groundwater recharge decreasing trend as a response to changes in precipitation[197]. 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[198]. While not included in the formal risk assessment due to the absence of climate projections, other studies provide useful context, showing that extensive areas in coastal zones (e.g., the Nile Delta) may become submerged, with coastlines shifting inland by several kilometers[199]. Such changes are associated with salinization effects that negatively influence survival and reproduction in soil invertebrates[200,201], and trigger avoidance behavior in species like earthworms[202].

Effects of the methodological limitations on the risk assessment

Our methodological approach has certain limitations that should be acknowledged. First, the geographic and temporal disparities in available studies introduce biases, as most projections originate from the northern Mediterranean, with limited data from the southern and eastern sub-basins. This imbalance affects the regional representativeness of our findings. Second, our reliance on scenario-based projections means that studies focused solely on past or present observations were excluded from the risk assessment, potentially overlooking important baseline trends. Third, while we aimed to integrate multi-stressor interactions, most available studies assess individual climate drivers rather than their combined effects, limiting our ability to quantify synergistic or antagonistic responses. Additionally, uncertainties inherent in modeling, laboratory experiments, and mesocosm studies—such as variations in experimental duration, scale, and environmental representativeness—may influence projected impacts. To mitigate these limitations, we assigned confidence levels based on study agreement and methodological rigor, but we recognize the need for further research to improve the granularity and comprehensiveness of climate risk assessments in the Mediterranean.

Conclusions

In order to determine the projected future risks in the Mediterranean Sea and its marine and coastal ecosystems, we conducted a systematic risk assessment based on the available literature, following the IPCC methodology. Our synthesis reveals a diversity of responses among key Mediterranean habitats and ecosystems to various climate-related hazards across different warming scenarios. When the increase in sea surface temperature (ΔSST) exceeds 0.8 °C relative to the 1976–2005 baseline, risks are projected to be high to very high (low to medium confidence) for seagrass meadows and seaweeds, and moderate to high for fish populations. Epipelagic ecosystems are projected to be more resilient, with risks ranging from undetectable to moderate. For coralligenous assemblages, moderate to high risks are projected when ΔSST surpasses 3.1 °C (medium confidence). Additionally, our assessment shows that all examined coastal ecosystems are likely to experience high to very high risks beyond the 0.8 °C threshold (medium to high confidence), except for rocky shores, which appear more resilient, with a slower risk escalation from moderate to high (medium confidence). These results reflect patterns consistently reported across the literature and underscore the urgency of addressing climate-driven risks in the region's most sensitive habitats.

Similar to global trends, all Mediterranean coastal ecosystems are projected to face higher risk levels than open marine ecosystems, partly due to their exposure to multiple anthropogenic stressors, including coastal development, pollution, and resource overexploitation, which intensify the impacts of climate-driven changes. 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 assessment also highlights a remarkable gap in studies projecting the future response of key ecosystems and biological groups such as deep-sea habitats, megafaunal populations, seaweeds, and salt marshes. Additionally, the lack of comprehensive baseline data and long-term observational studies significantly constrains the reliability and interpretation of these projections. Addressing these foundational gaps is essential to better understand current ecosystem conditions, assess changes over time, and improve the accuracy of future risk assessments. Furthermore, our findings underscore a significant geographical imbalance, with most studies being Euro-centric and predominantly focused 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.

Directions for future research and applications

To enhance the scientific understanding and management of climate change risks on Mediterranean marine and coastal ecosystems, we propose the following directions for future research and applications. These recommendations address key gaps identified during this review process and aim to guide effective policymaking and adaptive management strategies. By addressing the highlighted gaps, future studies can significantly contribute to more accurate risk assessments, effective management practices, and informed policymaking.

1. Increased Granularity and Regional Specificity.

The Mediterranean Sea's ecological diversity necessitates region-specific analyses to account for its heterogeneous sub-basins. Future research should **conduct** detailed, sub-regional assessments to capture the unique oceanographic and ecological dynamics of the Western, Central, and Eastern Mediterranean basins, **utilize** high-resolution climate models to provide localized projections of environmental stressors, such as sea temperature rise, marine heatwaves, and ocean acidification, and **investigate** the species-specific responses within different habitats to improve predictions of ecosystem resilience and vulnerability.

2. Methodological Enhancements in Risk Assessment

To strengthen the robustness and transparency of risk assessments, future studies should **implement** standardized systematic review protocols with clear inclusion and exclusion criteria to ensure consistency and reproducibility, **expand** the use of the IPCC risk framework, explicitly defining and quantifying risk as a function of hazard, exposure, and vulnerability, and **integrate** cross-validation techniques that compare model projections with in-situ observations, mesocosm experiments, and historical trend analyses.

3. Addressing Uncertainties and Multi-Stressor Interactions

A comprehensive understanding of climate risks requires rigorous examination of uncertainties and stressor interactions. Thus, we recommend **quantifying** uncertainties associated with different methodologies, including modeling projections, laboratory experiments, and mesocosm studies, **investigating** synergistic and antagonistic interactions among multiple climate-related stressors, such as warming, acidification, deoxygenation, and sea level rise, and **utilizing** advanced ecosystem modeling approaches that simulate complex multi-stressor scenarios, thereby enhancing predictive accuracy.

4. Comprehensive Literature Integration and Gap Analysis

To address geographic and thematic disparities in existing research, we suggest **expanding** research efforts in underrepresented regions, particularly in the Eastern and Southern Mediterranean sub-basins, **promoting** cross-disciplinary collaboration to incorporate socio-economic, cultural, and governance dimensions into climate risk assessments, and **developing** comprehensive meta-analyses that synthesize findings across disparate studies to provide unified risk narratives.

5. Policy and Management Implications

To bridge the gap between science and policy, future applications should **develop** region-specific adaptation strategies that account for the socio-economic contexts of vulnerable communities, **implement** ecosystem-based management (EBM) frameworks to address the cumulative impacts of climate change and non-climatic stressors, such as pollution and overfishing, **enhance** transboundary cooperation among Mediterranean countries to support coordinated conservation efforts and marine spatial planning.

6. Recommendations for Future Research Directions.

To advance the field and support evidence-based decision-making, future research should focus on:

- Multi-stressor experimental studies that quantify cumulative impacts on species interactions, biodiversity, and ecosystem functions.
- Spatially explicit vulnerability mapping to identify high-risk areas and inform targeted conservation strategies.
- Integrative modeling approaches that link ecological risks with socio-economic impacts, enhancing the relevance of scientific findings for policy development.

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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Author contributions

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. A.H. prepared the references' list. All authors contributed to the review and finalization of the manuscript.

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