Chapter

Perspective Chapter: The Mediterranean Sea in a Changing Planet – Combining Field Observations with Emerging Technologies

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Abstract

Despite an increasingly complex global geopolitical scenario and the emerging challenges science is facing, the evidence-based information about a changing planet cannot be ignored. The international scientific community has a huge social responsibility, both for the future of the Planet and humankind itself. Nowadays, the approach to environmental sciences has deeply changed from the last few decades. Emerging technologies, legally-binding frameworks at a global scale (e.g., the BBNJ Agreement), and the spread of science diplomacy help us expand knowledge boundaries and tackle some of the ongoing issues due to the multiple planetary crises. The Mediterranean region has historically been subject to human pressures, and now we are facing all the consequences. Recently, EU guidelines for key marine and coastal habitat restoration were released, and many dissemination and outreach initiatives, aligned with field activities, are ongoing in an attempt to create a wiser relationship within the Mediterranean ecoregion. This is not only a science-driven perspective but also something emerging from cultural and daily habits, relying on those commonalities and traditions that make the relationship between cultural and natural heritage absolutely crucial. The Mediterranean scientific community has strong and long-lasting traditions, but the challenges we are facing require a higher level of integration. The emerging technologies enable the aimed infrastructure for the needed extensive data collection and the consequent large datasets interpretation, albeit in some areas we still lack the knowledge and the expertise needed to make this approach effective in the long term.

Keywords: digital twins, monitoring, marine biodiversity, restoration: Mediterranean Sea, climate change, endangered species

1. Introduction

The Mediterranean Sea is a global biodiversity hotspot, hosting 4–18% of all marine species – including 10,000–12,000 distinct species with 20–30% endemism – in less than 1% of the global ocean surface [1]. This highly oligotrophic (nutrient-poor) ecosystem is characterized by unique habitats like *Posidonia oceanica* seagrass meadows and coralligenous communities, which face severe threats from climate change, industrial fishing, and pollution. A multidecadal environmental monitoring tradition has made many Mediterranean Sea areas well studied, but there are still some knowledge gaps [2]. Here, the development of technologies for large dataset analysis and the use of historical records integrated with remotely sensed data can be combined to predict future scenarios and adapt proper management strategies. The ongoing accelerated change demands a transition from traditional monitoring to a more integrative, dynamic approach. Emerging technologies, including satellite remote sensing for real-time monitoring of pressing issues such as rising temperatures and sea-level rise, AI-driven models for predicting ocean dynamics, and eDNA metabarcoding to detect invasive species, are redefining our capacity to study this highly impacted sea. By combining these high-tech tools with continuous, long-term field observations, researchers can better understand the synergistic impacts of climatic and anthropogenic pressures – such as marine heatwaves, pollution, and Suez Canal-driven species influxes. The upcoming challenge will be to make it in a balanced way to integrate technological advancements into a socio-economically sustainable development of related monitoring plans while safeguarding an acceptable level of expert engagement and occupational opportunities for those with the necessary cultural background to tackle the ongoing challenges. Envisioning an integrated Mediterranean Sea-observing system combining traditional field stations, autonomous platforms, satellites, and citizen networks is aligned with EU and Barcelona-Convention directives. In this perspective, emerging technologies are not an end in themselves but enablers of existing legal obligations – making enforcement fairer, monitoring more democratic, and science more responsive to a rapidly changing planet.

2. Methodology and literature review

The overall analysis and review of data hereby presented were conducted through a systematic literature review (PRISMA protocol), integrating relevant peer-reviewed literature (Web of Science, Scopus) published on the Mediterranean ecoregion area from 2010 to 2026, and incorporating data visualization and geospatial processing tools. Specifically, the investigated resources included quantitative analysis tools such as Copernicus and Mercator Ocean for oceanographic modeling, EDITO and EMODnet for bathymetry, habitat mapping, and human activities, as well as GIS software for raster data elaboration on biodiversity hotspots and climate impacts. Derivative metrics were identified to highlight climatic trends, resilience indexes, and projective scenarios, including the SST (Sea Surface Temperature) to describe heat waves and warming scenarios. The author's personal research and findings also included the results and data presented at recently attended events and conferences focused on habitat mapping, biodiversity trends, monitoring strategies, and climate impacts.

3. Environmental changes in the Mediterranean Sea and multiple planetary crises

The Mediterranean Sea stands out for its high biodiversity and unique hydrology compared to other semi-enclosed or marginal seas like the Black Sea, Baltic Sea, and Red Sea. These tables highlight key numerical differences in physical features, biodiversity, and other aspects. The Mediterranean's greater depth and higher salinity stem from high evaporation exceeding precipitation and runoff, showing elevated levels around 38 psu due to its evaporative nature [3–6] [**Table 1**].

Another key aspect is the Mediterranean's capacity to host a disproportionate species richness for its size, with elevated endemism stemming from its geological history. The Mediterranean Sea basin's specificity makes it a biodiversity hotspot despite its typically oligotrophic conditions [7] [**Table 2**].

From an oceanographic perspective, the Mediterranean Sea differs from other similar basins also due to the higher complexity in terms of concurrent water masses involved in the overall regional water circulation (**Figure 1**) [8].

These details underscore the Mediterranean's complexity from thermohaline forcing, versus simpler stratification in fresher basins like the Baltic or the Black and Red Sea [8] [**Table 3**].

In the last few years, the exacerbating consequences of climate change, multiple planetary crises, and the higher frequency of extreme events have made the Mediterranean Sea region more prone to events we weren't used to experiencing before [9–12]. In the perspective of the multiple challenges due to climate change, biodiversity loss, and pollution, the key emerging perspective is that everything is, more than ever, interconnected (**Figure 2**). The Mediterranean Sea faces profound environmental changes driven by the triple planetary crisis of climate change,

Sea	Surface area (km^2)	Max depth (m)	Avg depth (m)	Avg surface salinity (psu)
Mediterranean	2,500,000	5,267	1,500	38
Black Sea	436,400	2,212	1,190	17–18
Baltic Sea	377,000	459	55	7–8 (surface)
Red Sea	438,000	3,040	490	40–41 (higher in north)

Table 1.
Numerical differences in physical features of Mediterranean Sea [3] Compared to other similar sea basins including: Black Sea [4], Baltic Sea [5], and Red Sea [6].

Sea	Total marine species (approx.)	Endemism rate (%)	Benthic invertebrates (approx.)
Mediterranean	17,000	20–30	6,000
Black Sea	~2,000 (est. from benthic)	Low (< 5)	800
Baltic Sea	~4,000	Low	N/A
Red Sea	~3,000 (high for coral)	~15 (fish)	N/A

Table 2.
Biodiversity metrics including total number of Marine species, Endemism rate, and biodiversity invertebrate approximate estimates. The data are considered in comparison with similar Sea basins including: Black Sea, Baltic Sea, and Red Sea [7].

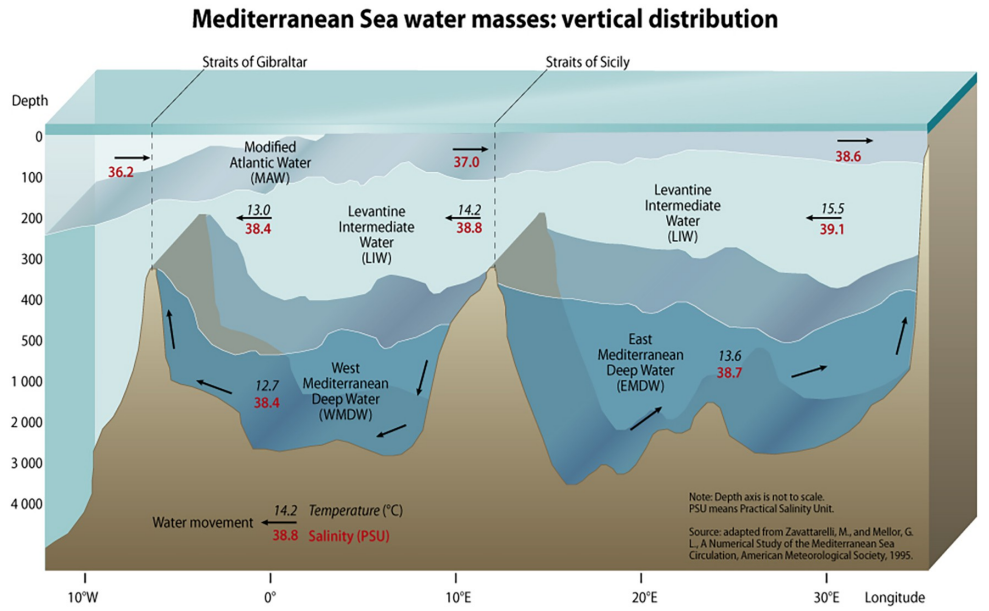

Figure 1.
Mediterranean Sea water masses: vertical distribution [8].

biodiversity loss, and pollution, which interact to threaten its unique ecosystems [1e]. As a semi-enclosed basin warming faster than the global average, the Mediterranean is considered a climate change hotspot. According to the latest Ocean State Report, it recorded its hottest periods in 2025, with July sea surface temperatures averaging 26.9 °C and marine heatwaves affecting 98% of the basin in the first half of the year [13].

Rising temperatures, sea-level rise, and acidification disrupt food webs and coastal habitats. Marine heatwaves since 2015 have caused mass mortalities in over 50 species, including corals and sponges, while projections under high-emission scenarios predict 2.7–3.8 °C of additional warming by 2100, leading, for instance, to seagrass loss and over a 60% decline in sea turtle nesting sites [14]. Deoxygenation and reduced primary production further compound risks, particularly in oligotrophic eastern waters.

On the other side, overfishing remains the world's highest in the Mediterranean, though recent FAO data shows a decade-low, with habitat degradation and pollution as top threats [15]. Microplastics form a "plastisphere" richer in microbes than the surrounding seawater [16, 17], while eutrophication creates dead zones, and invasive species such as the Atlantic blue crabs (*Callinectes sapidus, Portunus segnis*) proliferate during heatwaves, collapsing local fisheries due to their strength in competing for resources with native species [18–20]. The high presence of anthropogenic activities also results in geoaccumulation issues, posing significant risks for marine organisms and human well-being related to high concentrations of heavy metals and metal mixture exposure [21].

Considering the benthic environment, an iconic example is that of *Posidonia* seagrass beds. Despite their role being vital for carbon sequestration, they have lost 90% of habitat coverage in polluted areas like the Gulf of Gabes in Tunisia, mainly

Sea (water masses count)	Key water masses	Typical salinity (psu)	Typical temp (°C)	Depth range (m)	Notes/formation
Mediterranean (21)	Modified Atlantic Water (MAW)	36.2–38.6	12–18	0–200	Surface inflow via Gibraltar grida
	Levantine Intermediate Water (LIW)	38.4–39.1	13–15.5	200–800	Forms in Levantine Basin grida
	Western Med Deep Water (WMDW)	38.4	12.7	> 1000	Gulf of Lions winter convection grida
	Eastern Med Deep Water (EMDW)	38.7	13.6	> 1000	Aegean and Adriatic origins grida
Black Sea (5)	Cold Intermediate Layer (CIL)	17–18	6–8 (summer min)	50–150	Winter cooling, oxic layer ouci.dntb.go
	Upper layer (river-influenced)	< 18	10–25	0–150	Fresh from Danube etc., anoxic below usni
	Deep anoxic layer	22	~ 8.5	> 200	Bosporus saline inflow wikipedia
Baltic Sea (~ 6-8)	Kattegat Surface Water	25–32	5–15	Surface	Saline inflow from North Sea wikipedia
	Central Baltic Proper Surface	5–10	2–15	0–60	Brackish, river-dominated archive. iwlearn
	Baltic Proper Deep Water	10–15	2–5	> 60	Salt intrusions, hypoxic archive. iwlearn
	Gulf of Bothnia Water	0–7	0–10	Varies	Near-fresh, stratified archive.iwlearn
Red Sea (4 primary)	Red Sea Surface Water (RSSW)	40–42	20–30	0–150	Evaporation-driven villasmunta
	Gulf of Aden Intermediate Water (GAIW)	35–36	15–20	150–400	Inflow mixing meet-ingorganizer. copernicus
	Red Sea Deep Water (RSDW)	40.5 +	21.5	> 400	Central/southern formation iow

Table 3.
Water masses count for each sea basin and related notes on formation processes, typical salinity (psu), temperature (°C), depth range (m), and notes on formation origin [8].

due to industrial discharges [22]. Additionally, this Mediterranean Sea habitat-forming species is still being affected by anchoring and physical damage, even in protected areas where there is still a lack of proper enforcement of many extant regulations [23].

3.1 Shifting baseline in Mediterranean ecosystems ecological knowledge

Despite a long-standing tradition in Mediterranean marine ecosystem research, every time a new cohort of marine scientists approaches the study of the marine

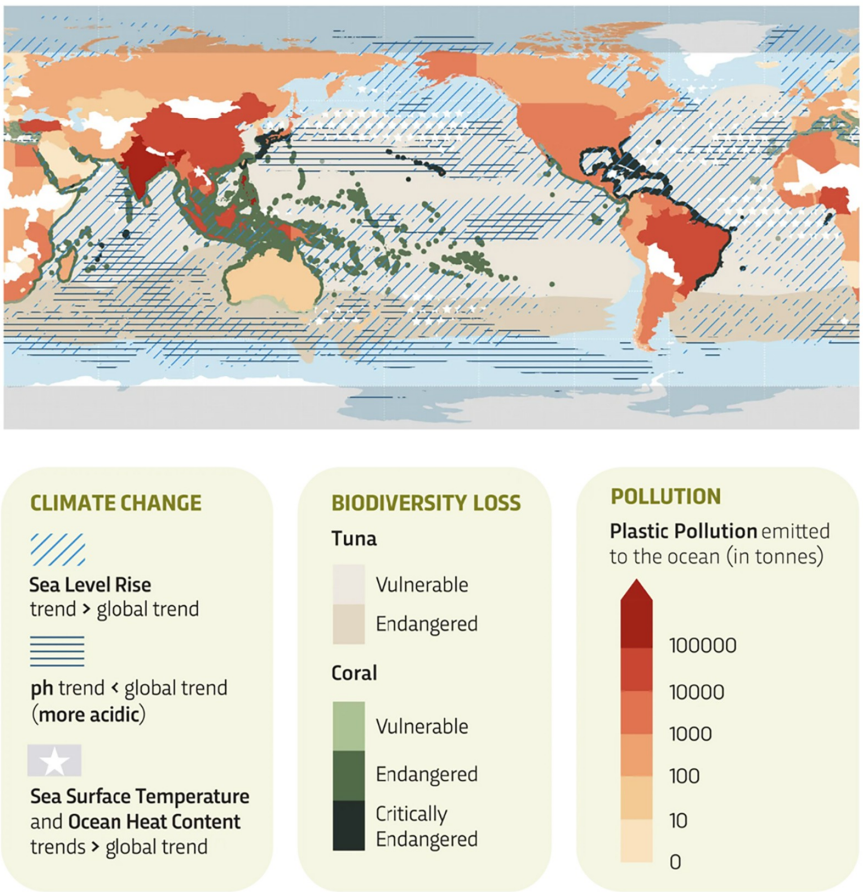

Figure 2.
An illustration of what the UN has termed the 'triple planetary crisis' of climate change, biodiversity loss, and plastic pollution across the global ocean [13].

realm, we are prone to consider the current status of knowledge as the reference baseline, implicitly accepting the observed degraded state as "normal," due to a lack of memory of healthier past conditions. This is an old issue, already highlighted by the prominent fisheries scientist D. Pauly in 1995 [24]. The shifting baseline is still valid in the Mediterranean Sea, where the phenomenon is particularly evident in overexploited fisheries and habitats, and where fishers' perceptions reveal long-term declines masked by a sort of generational amnesia [25, 26]. Shifting baselines can lead to progressively lower conservation targets as environmental memory fades across generations. Younger fishers, for instance, may view current depleted stocks as the baseline, underestimating historical abundance. For this reason, Fishers' Ecological Knowledge (FEK) remains vital for establishing baselines where scientific data is scarce [27, 28]. The same may occur with biological invasions, such as those involving invasive alien species like the blue crabs (e.g., *Callinectes sapidus, Portunus segnis)* or the more recently detected red crab (e.g., *Gonioinfradens giardi).* As happened with the first record of blue crabs a few years ago, the untimely responsiveness at the policy level, tied to the lack of properly adopted management

measures, allowed species never seen before in the Mediterranean Sea basin to occur at a higher rate. This led to the weakening of some native species populations and, in some areas, their progressive replacement, making it necessary to adapt traditional fisheries strategies (**Figure 3**). This occurred at such a high rate that some of the current marine scientists have no memory of all the native populations in certain areas. In the absence of historical trend records and archival data, this may lead to misinterpretations of biological community composition, with consequent biases in the shaping of management policies [29].

Consequently, each new generation of scientists, managers, and users accepts the degraded state of an ecosystem they encounter for the first time as the "normal" or "healthy" condition, rather than comparing it to an earlier, less-impacted state. This means long-term declines in fish populations, reef structure integrity, and marine biodiversity trends are often underestimated or normalized because the reference point for "what should be here" keeps sliding downward over time. In marine examples such as coral reefs and large-scale fisheries, shifting baselines lead to several problems. Conservation complacency is a typical example. In this case, efforts may only aim to restore ecosystems to a state that is still heavily impacted, instead of toward a more historically intact condition [30]. Another issue is related to policy and management bias: given that management targets and legal thresholds are often based on recent, already-degraded data, regulations may fail to reverse long-term decline.

To counteract this, marine ecologists and conservationists increasingly integrate:

- Historical and palaeo-data (archeology, sediment cores, old records) are used to reconstruct pre-impact conditions.

- Local and traditional knowledge extends the temporal window beyond scientific monitoring.

Figure 3.
Small-scale fisheries operating in the coastal area of Aegadian Islands MPA. Image credits: M. Gaglioti.

- Shifting baselines–aware thresholds: Framing targets and thresholds within longer-term ecological and social histories, rather than using only recent, depleted data as the reference.

3.2 Invasive alien species and the need for effective early warning systems

Invasive alien species outbreaks disrupt biodiversity, fisheries, and economies (with significant damages and harvesting losses), contributing to habitat degradation and management issues [31]. Mitigation via early detection, culling, and regional cooperation (e.g., ACCOBAMS frameworks) is important to contain the effects of uncontrolled expansions (**Figure 4**). Among the main issues a properly developed early warning system may help to detect, there are:

1. Ecosystem health (biodiversity loss, regime shifts, ecosystem-service degradation);

2. Human and animal health (disease vectors, zoonoses, allergens, toxins);

3. Blue/green economy and livelihoods (fisheries, aquaculture, tourism, coastal protection).

Due to the dramatically accelerating rate of invasive alien species introductions and the sheer magnitude of shipping traffic, the Mediterranean Sea may be considered a true hotspot of marine bioinvasions. The complexity of interactions between native and invasive species, along with the associated resulting impacts, makes environmental management of such an issue particularly difficult, requiring a higher level of collaboration between researchers, resource management agencies, and policy makers to ameliorate the effectiveness of the existing invasive species management procedures, addressing the gaps identified so far [34].

Figure 4.
Gonioinfradens Giardi and the Physalia Physalis sighted in Aegadian Islands MPA (Favignana Island); (Image credits: WORMS [32], Aegadian Islands MPA, and A. Pecorilla [33]. Used with permission).

4. Extreme events and emerging earth observation tools

The occurrence of biological invasions is merely a consequence in a Mediterranean region facing intensifying extreme events driven by climate change, including marine heatwaves, heavy floods, and storms, with profound impacts on marine ecosystems and structural cascading effects relevant to conservation efforts. These events have surged in frequency and intensity in recent years and are expected to intensify in the upcoming years, according to simulated data [35]. An example is that of macroalgal forests facing the effects of the climate crisis [36]. This is an ecologically relevant issue, considering macroalgal forests' role in primary production, climate change mitigation, and their function as efficient storage sites for carbon sequestration. As blue carbon sinks, their CO_2 absorption efficiency is 20–40 times higher than that of terrestrial forests [37]. The equivalent of macroalgal forest degradation can also occur in animal species characterizing benthic marine environments, such as hard-corals, sponges, or other calcifying organisms like bryozoans.

Nowadays, the development of new technologies has made the long-term monitoring of many of these phenomena more feasible, integrating field data with remotely-sensed observations. Among the key event types detectable with rapidly expanding visualization tools (e.g., Marine Copernicus, EDITO, Mercator Ocean infrastructures, **Figure 5**) there are:

- Marine heatwaves (MHWs): Recurrent since 2015, affecting all basins and causing mass mortalities in over 50 species, such as corals and sponges, across thousands of kilometers of coastline. The northern areas, like the Gulf of Lion and Adriatic, experience the most intense and frequent events, while longer ones occur in the Levantine Sea.

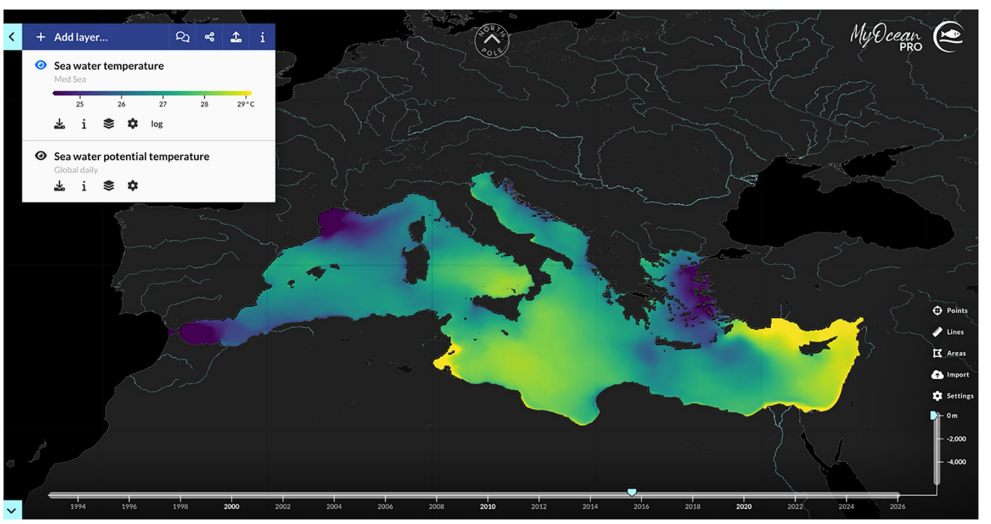

Figure 5.
Sea surface temperature trends in the Mediterranean Sea detected from Copernicus Marine Service and displayed on My Ocean Pro Viewer: https://data.marine.copernicus.eu/viewer [38]. Used with permission.

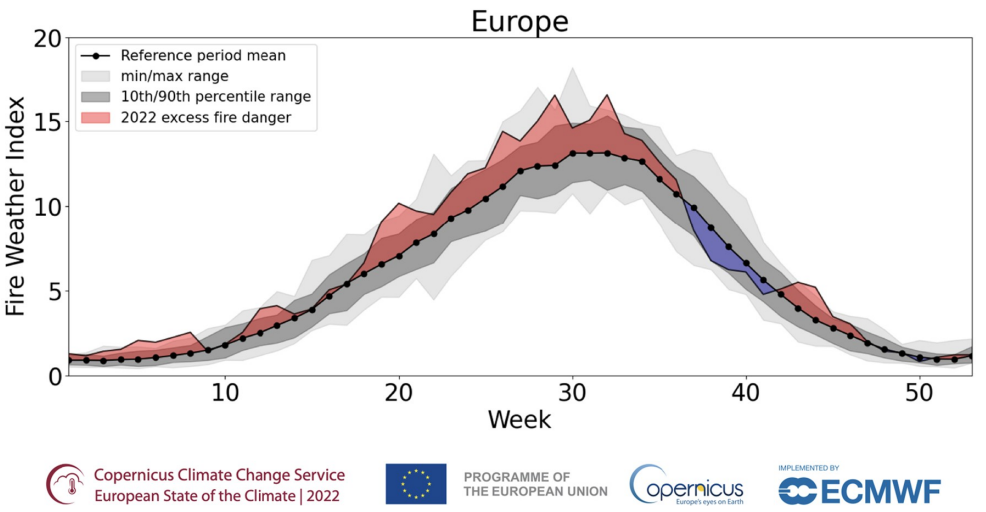

Figure 6.
Fire Weather Index weekly average anomalies for Europe in 2022 (positive values in red and negative in blue) relative to the average for the 1991–2020 reference period (dotted black line; minimum and maximum – light gray shading; 10th to 90th percentile – dark gray shading). Data source: FWI based on ERA5. Credit: Copernicus EMS/ECMWF [39]. Used with permission.

- Atmospheric heatwaves and droughts: The 2022–2023 summers hit record anomalies of + 3.6 °C and + 2.9 °C, exceeding natural variability, with co-occurring fires and ecological disruptions (**Figure 6**).

- Extreme precipitation and floods: One example is the event registered in October 2024 in Valencia. This event was amplified by human-induced warming and warm sea surface temperatures. Similarly, in January 2026, forecasts warned of 200–300 mm of rain in Italy, Sicily, and Algeria. Storm Daniel in 2023 brought > 1,000 mm rain to Greece and Libya, causing thousands of deaths. The Cyclone Harry in early 2026 is another example of an extreme event, causing damage along the shores of Sicily, Sardinia, and Calabria, with wind speeds up to 130 km/h, heavy rainfall, and wave heights up to 10 m (**Figure 7**).

In this complex and rapidly changing scenario, even the development of large-scale observation datasets and large data centers for monitoring data analysis is a daily, pressing challenge. As clearly outlined in the 9th Ocean State Report (OSR9) [13], the impacts of ocean change are linked not just to marine ecosystems but to numerous social, economic, and cultural facets of human society. The Starfish Barometer [40] (**Figure 8**), launched on World Ocean Day 2025, offers an accessible, science-based annual snapshot of the ocean's state and its vital connection with humanity. For this reason, it is crucial for us, as marine scientists, to contribute to restoring not only a healthy marine ecosystem but also to invest in a good relationship between our society and the ocean, to better address the ongoing and upcoming challenges.

MHWs and cold spells are well-known to disrupt ecosystems, with the 2003 and 2015–2018 events notable for widespread activity, especially in western and

Figure 7.
The devastating effects of the Harry cyclone along the Sicilian coasts in early 2026 (Photo credits: ANSA. Used with permission).

northern basins. These phenomena threaten biodiversity hotspots, aligning with Mediterranean conservation priorities such as protected areas. Rising sea temperatures, which are warming 20% faster than global averages, exacerbate mass mortalities and species shifts [41]. An example of this is observed in the coralligenous habitats of the Tavolara MPA, affecting scleractinians and gorgonians from depths of 15 up to 40 meters (**Figure 9**). These observations, described in a manual for divers conceived within the "Fins into the water" project [42] and leading to a coral restoration initiative in the same area, are just one example of similar occurrences observed across the entire Mediterranean Sea basin. Additionally, there are increasing periodical occurrences of invasive alien species, such as the recently detected Siphonophorus *Physalia physalia* (the so-called Portuguese Man-o-War) in the Aegadian Islands MPA in eastern Sicily, following previous sightings in other areas of the same region in the past [43]. After the highest historical occurrence registered in 2010, it seems that *P. physalia* sightings have increased in recent years, especially in the western Mediterranean between Spain and Sicily, often due to currents and winds pushing colonies through the Strait of Gibraltar [44, 45].

4.1 Disaster risk reduction and preparedness at Mediterranean Basin scale

Disaster Risk Reduction (DRR) and preparedness in the Mediterranean Sea hinge on integrating climate-adaptation planning, multi-hazard early-warning systems, and cross-border cooperation, because the basin combines high-risk geological hazards with dense coastal populations and climate-driven extremes [46, 47]. The ecological complexity of such highly anthropized areas as the Mediterranean Sea basin requires advanced computing skills and a multiperspective approach to tackle complex ecological and human-driven challenges. The use of emerging technology can widely support this need, improving our capacity to better predict and model future trends and what-if scenarios. As is the case of the EDITO modeling environment, applicable to marine plastic exposure through the *Marine Plastic Tracker* tool, providing essential data to decision-makers and scientists to develop mitigation strategies against marine pollution [48]. A similarly developed proof of concept targeting invasive alien species was presented at the latest Open Sea Lab 4.0 Hackathon in 2025 by an international team of young aspiring researchers and marine scientists. the "Blue crab" solution, as it was named, was awarded an

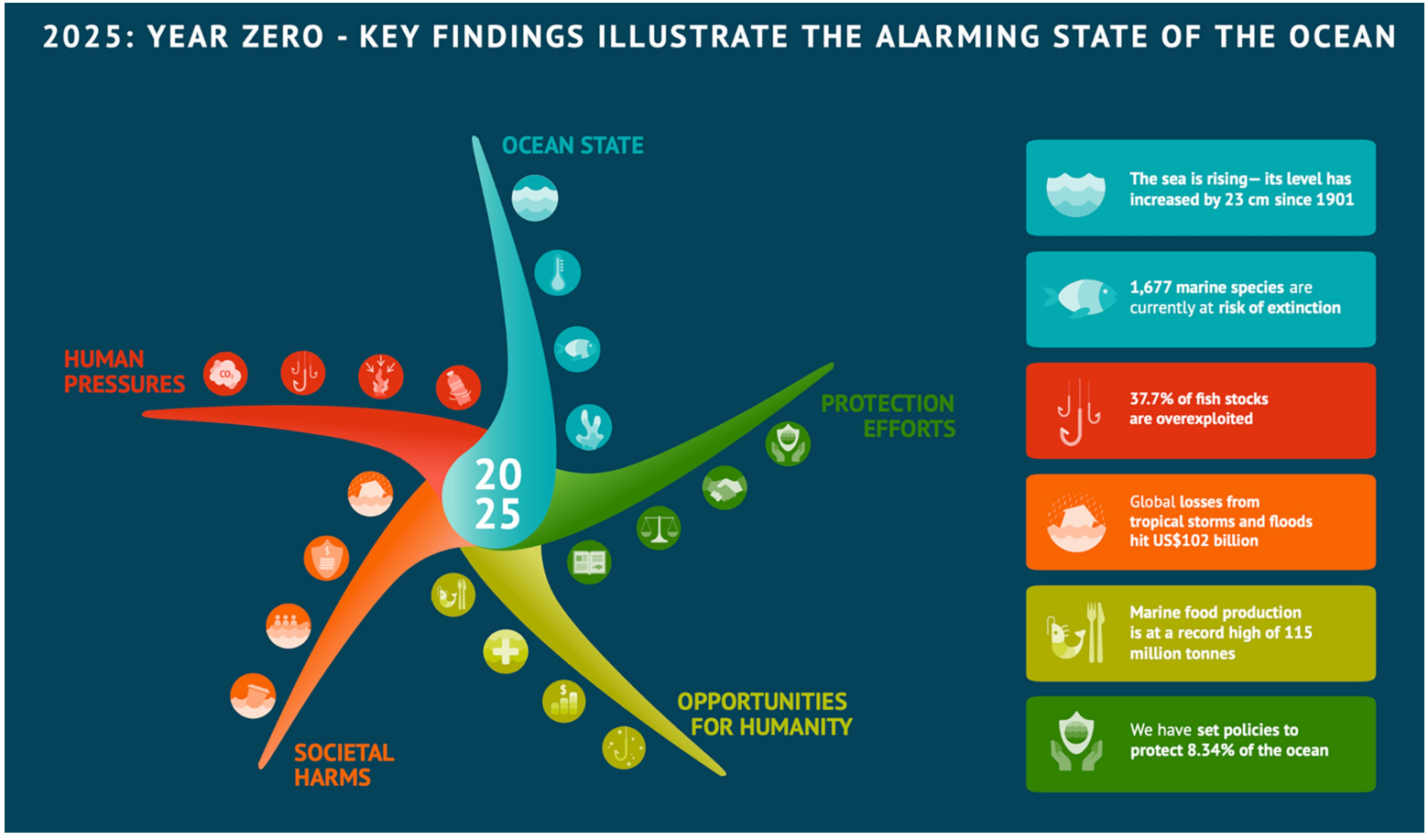

Figure 8.
The Starfish Barometer [40] emphasizes the two-way relationship between humanity and the ocean: We impact its future, and it shapes ours. the figures represent the most recent estimates available on 8 June 2025 (Copyright © Starfish Barometer). Used with permission.

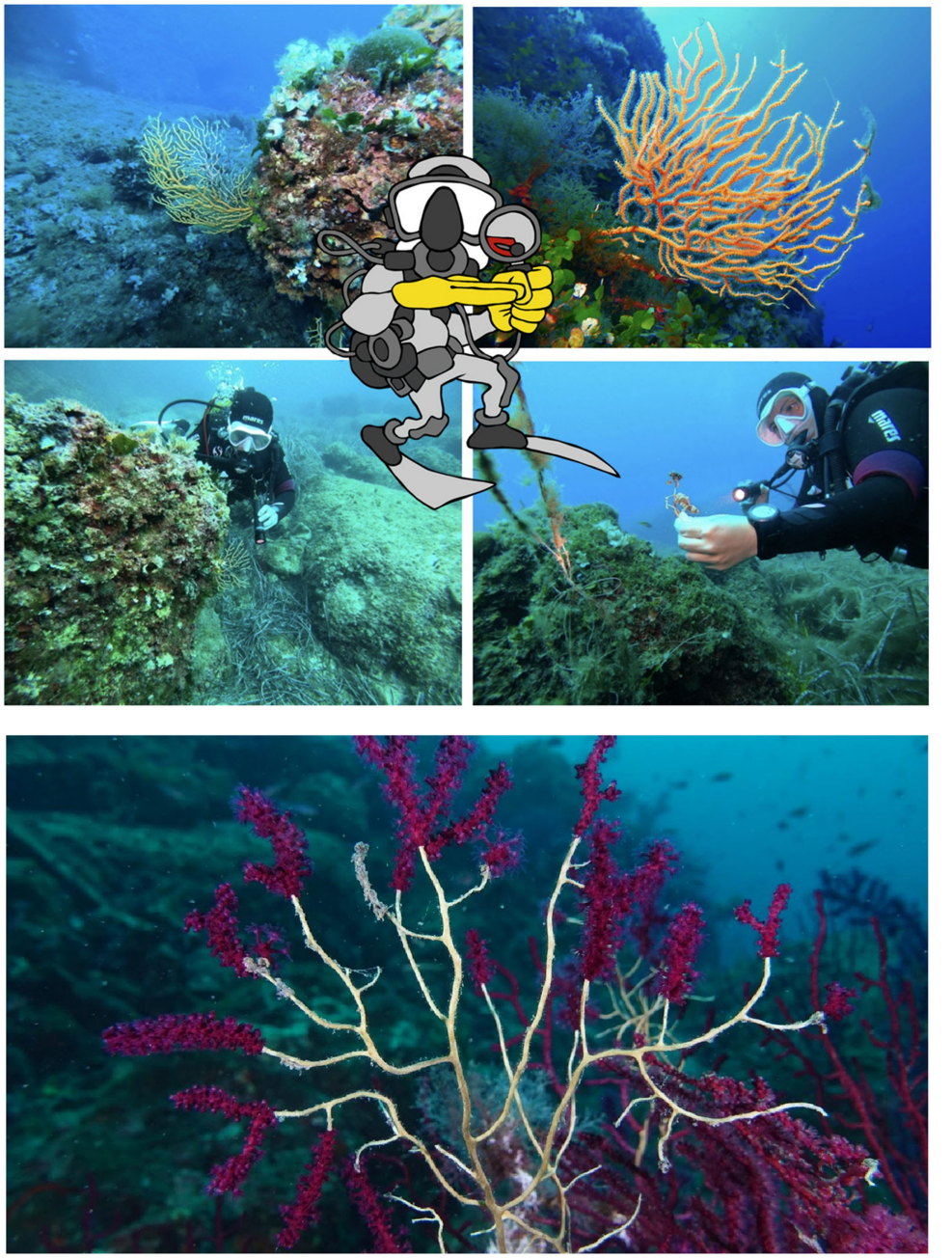

Figure 9.
Preliminary underwater sampling for habitat restoration project development in Tavolara MPA. An example of mortality event detected in the Gulf of Naples consequently to the summer heatwaves (Banco Di Santa Croce-2018). Used with permission.

innovation prize by a jury that included European Commission DG ENV and DG MARE representatives as well as marine experts [49].

5. Legal and policy frameworks shaping the Mediterranean sea's sustainable future

Regional efforts, like the updated Mediterranean strategy from COP24 (2025) [50], emphasize ecosystem-based management and climate adaptation, supporting EU goals for achieving a good environmental status by 2030. Initiatives such as ACCOBAMS [51] and BlueMissionMed [52] promote habitat restoration for vulnerable species and Ocean Literacy regional strategies [53], which are relevant to supporting conservation initiatives for protected areas and species like cephalopods. Stronger transboundary cooperation via MSFD is essential to counter these interconnected crises.

Several directives and regulations at the EU-level specifically cover or significantly affect the Mediterranean Sea, both through region-wide marine-environment law and targeted fisheries and pollution instruments. Among these are the Common Fisheries Policy with its Multiannual Plans (MAPs), the Marine Strategy Framework Directive (MSFD), and targeted pollution regulations such as the 2025 Mediterranean Emission Control Area (Med SOx ECA) [54–56]. The UNEP/MAP–Barcelona Convention system [57] serves as the comprehensive institutional, legal, and implementation framework that the Contracting Parties have adopted for concerted action to fulfill the vision of a healthy Mediterranean Sea and coast, which underpins sustainable development in the region. The Nagoya Protocol regulates access to genetic resources in the Mediterranean Sea, requiring prior informed consent (PIC) and mutually agreed terms (MAT) for research and commercial use. It ensures fair benefit-sharing for the use of marine genetic resources [58], applying to coastal, territorial, and seabed areas, while excluding international waters. Convention on Biological Diversity (CBD) [59], aiming to ensure the fair and equitable sharing of benefits arising from the utilization of genetic resources, is important for covering genetic resources and associated traditional knowledge, guiding access and compliance. Parties must adopt measures to ensure that genetic resources are used within their jurisdiction. The Nagoya Protocol [58] ensures fair access and benefit-sharing (ABS) for genetic resources used in Mediterranean Sea restoration projects [60], particularly in biotechnology and habitat rehabilitation, such as seaweed reforestation. It enforces legal compliance for researchers using marine organisms, requiring mutually agreed terms (MAT) to balance environmental restoration with sustainable use [61]. The recent adoption of the Nature Restoration Regulation and the consequent release of the first EU technical guidelines around some of the main marine habitats under the EU Habitat Directive, including habitats 1140, 1160, 1180, and 8330 [62–65], established the first milestones to provide clear guidance toward the upcoming policy implementation phase.

Among the latest achievements to facilitate an integrated monitoring of the marine environment, ensuring all the above-mentioned directives and regulations can be accomplished, is the recently announced Ocean Eye, unveiled during the European Ocean Days in Brussels in early March 2026 [66].

6. Outreach and education: A shared roadmap toward ocean literacy goals

As confirmed by the latest achievements, a rising momentum around Ocean Literacy is ongoing on a global scale, and the Mediterranean Sea region is no exception [67]. This effort targets the whole of society at every single level, engaging different kinds of stakeholders. Particularly useful is to address tailored programs according to the different society categories, including the voices of those who have been historically marginalized, while striving to deliver the Ocean Literacy message through engaging and innovative approaches [68]. Among these approaches, particularly relevant is the use of proper language by representatives of the scientific community to bridge the gap with the rest of civil society. Successful experiences have included educational programs targeting specific blue economy sectors (e.g., small-scale fisheries, diving, and other water sports sectors) as well as the formal education environment and school students (e.g., the Blue School program), which is vocationally devoted to outreach and education. However, this program has so far not adequately addressed "Blue skills" in students' formal curricula. The main goal of this global initiative is to create an emotional relationship between people and the marine environment where it does not yet exist, or to reinforce the existing one where it seems insufficiently tailored to current needs and conservation gaps [69]. Successful initiatives have been conducted in several contexts so far, including MPAs, National Parks, and Biosphere Reserves, but also beyond these formally protected areas. These efforts align with broader-scale conservation objectives and Education for Sustainable Development, as per the Other Effective Conservation Measures (OECMs) definition, targeting a wider range of rights-holders and stakeholders [70].

7. The linkage between natural and cultural heritage in the Mediterranean ecoregion

Natural and cultural heritage in the Mediterranean are fundamentally co-produced: millennia of human use of coasts and seas have shaped ecosystems and landscapes, while those same environments have generated distinctive maritime cultures, knowledge systems, and identities [71]. The Mediterranean has long been described as a "shared sea," where diverse peoples, religions, crafts, and arts are linked by a common maritime space, so that the sea itself becomes a core element of regional cultural identity [72]. The Mediterranean Sea boasts astonishing examples of industrial archeology and long-lasting traditions, deeply rooted in the seascape and landscape of islands, villages, and coastal areas [73]. An example is found within the Aegadian Islands MPA, specifically on Favignana Island (**Figure 10**) where half of the island is marked by hundreds of galleries, quarries, and settlements for tuna processing. Here, traditions, local workers' lives, and stories of exportation beyond local boundaries were shaped over the centuries [74]. All this is the result of the merging of geological features and wise artisan traditions, as well as human-driven impacts affecting the conservation status of such an outstanding heritage [75]. This inextricable connection makes such a unique heritage difficult to replicate elsewhere. Nowadays, this intrinsic value becomes a particularly

Figure 10.
An example of Mediterranean industrial archeology, the quarrels system on Favignana Island (Sicily); Image credits: Martina Gaglioti. Used with permission.

compelling reason to pursue a shared conservation strategy that embraces natural and cultural heritage at different levels [76].

Recently, the EU launched a European Ocean Pact. Similarly, at a regional level, someone suggested being oriented toward a "Mediterranean Pact" [77] to better address the existing gaps and develop a more effective common strategy at the regional level. This Pact is a historic milestone for the EU's deeper cooperation within the Mediterranean ecoregion, being based on the principles of co-ownership, co-creation, and joint responsibility. It takes a practical approach, focusing on concrete initiatives that will bring added value to people and economies on all sides of the Mediterranean. The aim is to create mutual benefits, from clean energy production to unlocking private investment. This aim will be achieved by mobilizing regional projects that create opportunities for both people and businesses, with a particular focus on young people, women, and small businesses.

Recent data highlighted how, beyond formal designations, effective management remains a persistent challenge. Only 23% of Mediterranean MPAs (n = 1154) have fully or partially implemented their management plans. While awareness of key pressures – including pollution and invasive species – is high, and around 40% of surveyed MPAs (n = 263) report taking action to mitigate these threats, other critical issues receive less attention. For example, just 10% of surveyed MPAs (n = 263) assess tourism carrying capacity, despite the intense seasonal pressure placed on many Mediterranean coastal areas [69].

The extant gaps in MPAs effectiveness highlight another pending issue: human livelihoods and cultural heritage in many areas of the Mediterranean ecoregion are also under pressure. European countries with high population densities (> 200 persons per km^2) near the coast are located near ocean areas subject to rapid sea level rise (**Figure 11**). Rising sea levels increase the risk of flooding and erosion in coastal areas – changes which affect Europe's coasts, home to 200 million people. Many UNESCO World Heritage sites found in Europe's low-lying coastal areas will be partially or

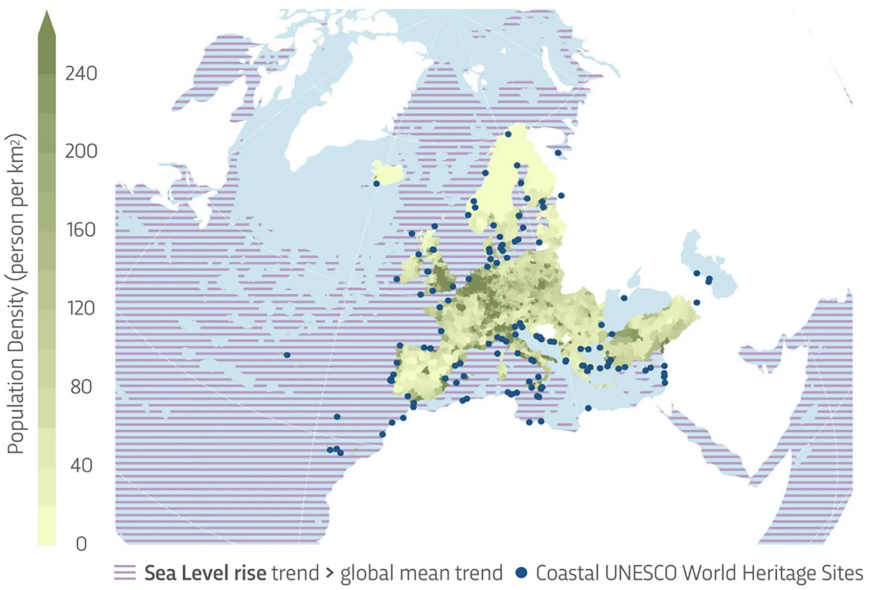

Figure 11.
Population density in European countries in 2023. Dark blue dots show coastal UNESCO heritage sites. Adapted from: Von Schuckmann et al., 2025. Copernicus Ocean State Report 9 [13]. Used with permission.

Figure 12.
The Venice Lagoon is an iconic example of the urgency to develop proper climate-adaptation strategies. (Photo credits: Martina Gaglioti. Used with permission).

totally flooded in the coming centuries or millennia. In this perspective, the adoption of proper climate adaptation strategies is more than ever essential [78].

8. Long-term research in the Mediterranean sea rapidly changing scenario

Due to its high vulnerability, in the Mediterranean Sea, long-term research focuses on tracking environmental changes, biodiversity, and human impacts in this

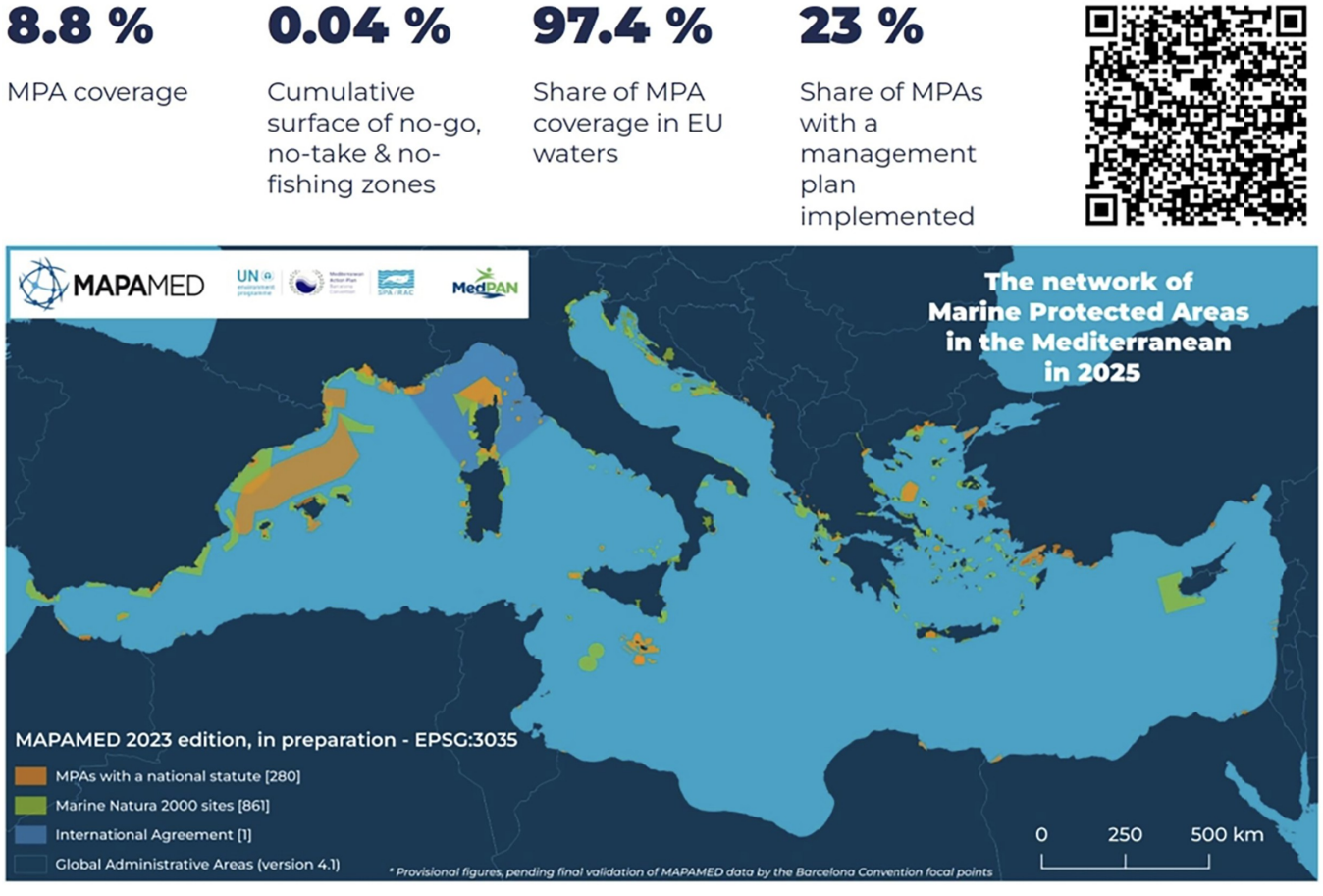

Figure 13.
Assessing the progress and effectiveness of marine protected areas in the Mediterranean, An overview from a recent resource [79]. https://drive.Google.Com/file/d/1osnhewrs2_oab2g3m4fgxyztqxintufz/view used with permission.

semi-enclosed basin. Key efforts emphasize hydrological shifts, ocean acidification, and conservation effectiveness. There are some iconic places, such as the Venice Lagoon (**Figure 12**), where a multidecadal tradition in hydrological monitoring is more than a research trend. It is highly connected to the extreme vulnerability to future climate scenarios, and sea level rise is just one of the most evident consequences of these increasingly high pressures.

Other studies are focused on ocean acidification, with the main goal of identifying gaps in geographic coverage and multi-stressor interactions, considering that Mediterranean waters acidify faster than the open ocean due to rapid circulation. Particularly relevant are studies focused on the effectiveness of Marine Protected Areas (**Figure 13**) and the EU Blue Parks initiative, which is aimed at creating a coordinated strategy to better address ongoing and future challenges in protected areas. Considering multiple stressors, including rising sea surface temperature (SST), invasive alien species, and increasing fishing pressures, is crucial to better address management priorities.

9. Conclusions

Many EU Directives require that genetic resource exploitation, particularly in marine protected areas (MPAs), includes benefits for the state or local communities. Despite the huge efforts conducted so far to shape conservation measures, implement monitoring programs, and carry out outreach programs, many representatives of local communities, particularly those located in insular regions, marginalized areas, and low-income countries along the Mediterranean shores, claim a lack of proper engagement and significant gaps in consultation processes, which do not always address bottom-up concerns. On the other hand, the Mediterranean Sea has always been identified as the cradle of civilization, with a common cultural heritage that includes history, traditions, food, and shared practices [71–73], which may serve as the key tool for leading the way toward a truly participatory approach to marine and coastal ecosystem conservation and restoration practices. This approach would not only address ecosystem-level concerns but also encompass human rights, ethical legacies, livelihoods, and shared security. The use of AI, emerging technologies, and the heritage of long-term monitoring efforts can be combined effectively. If this happens, considering the importance of keeping alive the human dimension and the added value of local traditions, ecological knowledge and past barriers can be overcome and the achievement of meaningful advancements and results can happen at a never seen before speed rate. We just have to trust and keep alive our critical thinking capacity, safeguarding it as much as we would do with our natural and cultural heritage.

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