# DEEP-SEA ECOSYSTEMS OF THE MEDITERRANEAN SEA:

## ECOLOGICAL IMPORTANCE AND VULNERABILITY TO CLIMATE CHANGE AND BOTTOM FISHING

APRIL 2026

# Credits

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# Summary

# Executive Summary

Mediterranean deep-sea ecosystems, particularly those between 600 m and 1000 m depth, are among the region's most ecologically valuable yet vulnerable environments. They host a mosaic of habitats, including cold-water coral reefs, sponge grounds, sea pen fields, bamboo coral (*Isidella elongata*) facies, submarine canyons, seamounts, and extensive soft-sediment plains. These systems support high biodiversity, important commercial species, and increased climate resilience, as natural, long-term reservoirs where carbon is stored. They are also highly vulnerable and slow to recover from damage, because they comprise slow-growing, long-lived species, with limited resilience to disturbance.

Bottom-contact fishing remains the most pervasive pressure on these habitats. In particular, bottom trawling removes habitat-forming species, alters sediment structure, and disrupts key linkages between the seafloor and the water column, with long-lasting impacts on ecosystem functioning and carbon burial. Evidence from the Mediterranean Sea shows that repeated bottom trawling leads to habitat degradation, reduced biomass of commercially important species, and loss of vulnerable marine ecosystems (VMEs). The Critically Endangered bamboo coral *Isidella elongata*, once widespread, now occurs only in scattered low-density populations due to trawling impacts.

Climate change is amplifying these pressures. Warming waters, deoxygenation, acidification, and reduced food supply are already affecting deep-sea species, with the Mediterranean warming faster than the global ocean. Habitat suitability models project significant declines in key VME taxa under high-emission scenarios, with suitable habitats shifting deeper and shrinking in several sub-regions. These trends threaten the long-term stability of deep-sea ecosystems and the fisheries they support.

Despite their vulnerability, deep-sea habitats may function as climate refugia, due to their relatively stable environmental conditions. However, this potential depends on maintaining ecological integrity. Degraded habitats lose structural complexity, functional redundancy, and carbon -storage capacity, reducing their ability to buffer climate impacts.

For the Mediterranean basin, strengthening deep-sea protection is both scientifically justified and strategically important. The region's deep-sea ecosystems underpin fisheries productivity, biodiversity conservation, and carbon-sequestration services. Expanding and reinforcing Fisheries Restricted Areas (FRAs), adopting depth-based closures, and implementing VME-specific protections would significantly reduce cumulative impacts and enhance ecosystem resilience. These actions would also support the Contracting Parties of the General Fisheries Commission for the Mediterranean (GFCM) in meeting international commitments under the Convention on Biological Diversity (CBD), Food and Agriculture Organization (FAO) guidelines, and the GFCM 2030 Strategy for sustainable fisheries and aquaculture in the Mediterranean and the Black Sea.

International experience from Regional Fisheries Management Organizations (RFMOs), demonstrates that precautionary, broad-scale measures to limit bottom-trawling impacts on deep-sea ecosystems are effective and feasible. Depth-based closures (e.g. trawl bans below 600-800 m), permanent VME/ Essential Fish Habitat (EFH) closures, and gear restrictions are widely adopted tools that reduce impacts in data-poor contexts. These measures are enforceable, compatible with existing monitoring systems (Vessel Monitoring System - VMS, Automatic Information System - AIS, Synthetic Aperture Radar - SAR), and aligned with United Nations General Assembly (UNGA) Resolutions and FAO VME guidelines.

# Glossary

**AIS (Automatic Identification System):** A satellite- and VHF-based vessel tracking system used to monitor maritime traffic, improve navigation safety, and support fisheries control and surveillance activities.

**Aphotic zone:** The part of the ocean where there is little or no sunlight. It is formally defined as the depths beyond which less than 1% of sunlight penetrates.

**Bioturbation:** Sediment mixing caused by benthic organisms, influencing oxygen penetration, nutrient cycling, and carbon burial efficiency.

**BPC (Benthic-Pelagic Coupling):** The ecological and biogeochemical exchange of energy, organic matter, and nutrients between the seabed and the overlying water column. This process regulates deep-sea productivity, carbon cycling, and food-web dynamics.

**CBD (Convention on Biological Diversity):** An international legally binding treaty aimed at conserving biodiversity, ensuring sustainable use of biological resources, and promoting equitable benefit-sharing.

**CCAMLR (Commission for the Conservation of Antarctic Marine Living Resources):** A Regional Fisheries Management Organisation (RMFO) established under the Antarctic Treaty System to conserve Antarctic marine living resources through ecosystem-based management approach.

**EMT (Eastern Mediterranean Transient):** A major oceanographic event (late 1980s–1995) involving shifts in deep-water formation, temperature, and salinity in the Eastern Mediterranean. EMT significantly altered deep-sea circulation and ecosystem functioning.

**ENM (Environmental Niche Modelling):** A modelling approach used to predict species distributions based on environmental variables and to project potential shifts under future climate scenarios.

**Epifauna:** Refers to animals that live on or are attached to the seafloor, with examples including corals, echinoderms, and sponges.

**EFH (Essential fish habitat):** All types of aquatic habitats that are necessary for fish to spawn, breed, feed, or grow to maturity.

**Euphotic zone:** The uppermost layer of a body of water that receives sunlight, allowing phytoplankton to carry out photosynthesis. The thickness of the euphotic zone varies with the intensity of sunlight as a function of season and latitude and with the degree of water turbidity.

**FAO (Food and Agriculture Organization of the United Nations):** A UN specialized agency that leads international efforts to defeat hunger, including providing global policy guidance and technical standards for topics that include sustainable fisheries management and protection of VMEs.

**FRA (Fisheries Restricted Area):** A GFCM spatial management measure establishing area-based restrictions on fishing activities, which may include gear limitations, effort controls, permanent and temporal closures to protect vulnerable habitats and EFH.

**GFCM (General Fisheries Commission for the Mediterranean):** An RFMO responsible for the sustainable development of aquaculture and the conservation and sustainable management of fisheries resources in the Mediterranean and the Black Sea.

**HSM (Habitat Suitability Modelling):** A predictive modelling approach based on species occurrence records and environmental variables, which is used to estimate and map suitable habitat, such as identifying potential climate refugia and VME hotspots.

**Infauna:** Invertebrates living within aquatic sediments, including organisms such as polychaetes, bivalves, and crustaceans, which are crucial for sediment reworking and influencing sediment dynamics through burrowing, feeding, and irrigation activities.

**IUCN (International Union for Conservation of Nature):** An international authority on biodiversity conservation responsible for the IUCN Red List of Threatened Species and for providing science-based conservation guidance.

**MTC (Mean Temperature of the Catch):** An indicator used to measure the impact of ocean warming on fisheries by calculating the average preferred temperature of species in a catch, weighted by their annual catch volume.

**MPA (Marine Protected Area):** A clearly defined marine area managed through legal or effective measures to ensure the long-term conservation of biodiversity, ecosystem services, and ecological integrity.

**NAFO (Northwest Atlantic Fisheries Organization):** An RFMO responsible for the conservation and sustainable management of fisheries resources in the Northwest Atlantic, including the protection of VMEs.

**NEAFC (North-East Atlantic Fisheries Commission):** An RFMO responsible for the conservation and sustainable management of fisheries resources in the Northeast Atlantic, including VME protection measures.

**OECMs (Other Effective Area-Based Conservation Measures):** A geographically defined area not designated as an MPA but managed to achieve long-term and effective in situ biodiversity conservation under the CBD framework.

**Oxic (layers):** Well-oxygenated surface waters in the sea (typically at depths of 0–50 m) where photosynthesis, mostly by phytoplankton, exceeds respiration, producing oxygen that sustains most marine life.

**RCP (Representative Concentration Pathway):** A set of greenhouse gas concentration trajectories used in climate models to represent different radiative forcing scenarios and project future climate conditions (e.g. RCP 8.5).

**Redox:** A type of chemical reaction in which the oxidation states of the reactants change. Oxidation is the loss of electrons or an increase in the oxidation state, while reduction is the gain of electrons or a decrease in the oxidation state. The oxidation and reduction processes occur simultaneously in the chemical reaction.

**RFMO (Regional Fisheries Management Organization):** An intergovernmental body mandated to regulate and manage fisheries in specific ocean regions, including the adoption of conservation measures to protect fish stocks and VMEs.

**SAR (Synthetic aperture radar):** A satellite-based radar system that enables vessel detection regardless of weather or daylight conditions, supporting fisheries monitoring, compliance, and maritime enforcement activities.

**SPRFMO (South Pacific Regional Fisheries Management Organisation):** A RFMO responsible for the conservation and sustainable management of fisheries resources in the South Pacific, including VME protection measures.

**Three-dimensional structure or framework:** In the context of marine sessile species, the volumetric complexity and physical, vertical arrangement created by organisms that live fixed to the seabed (e.g. corals, sponges, bryozoans). These frameworks function as "Marine Animal Forests" (MAFs), acting as ecosystem engineers that provide critical habitat, shelter, and nurseries for numerous other marine organisms, analogous to trees in a terrestrial forest.

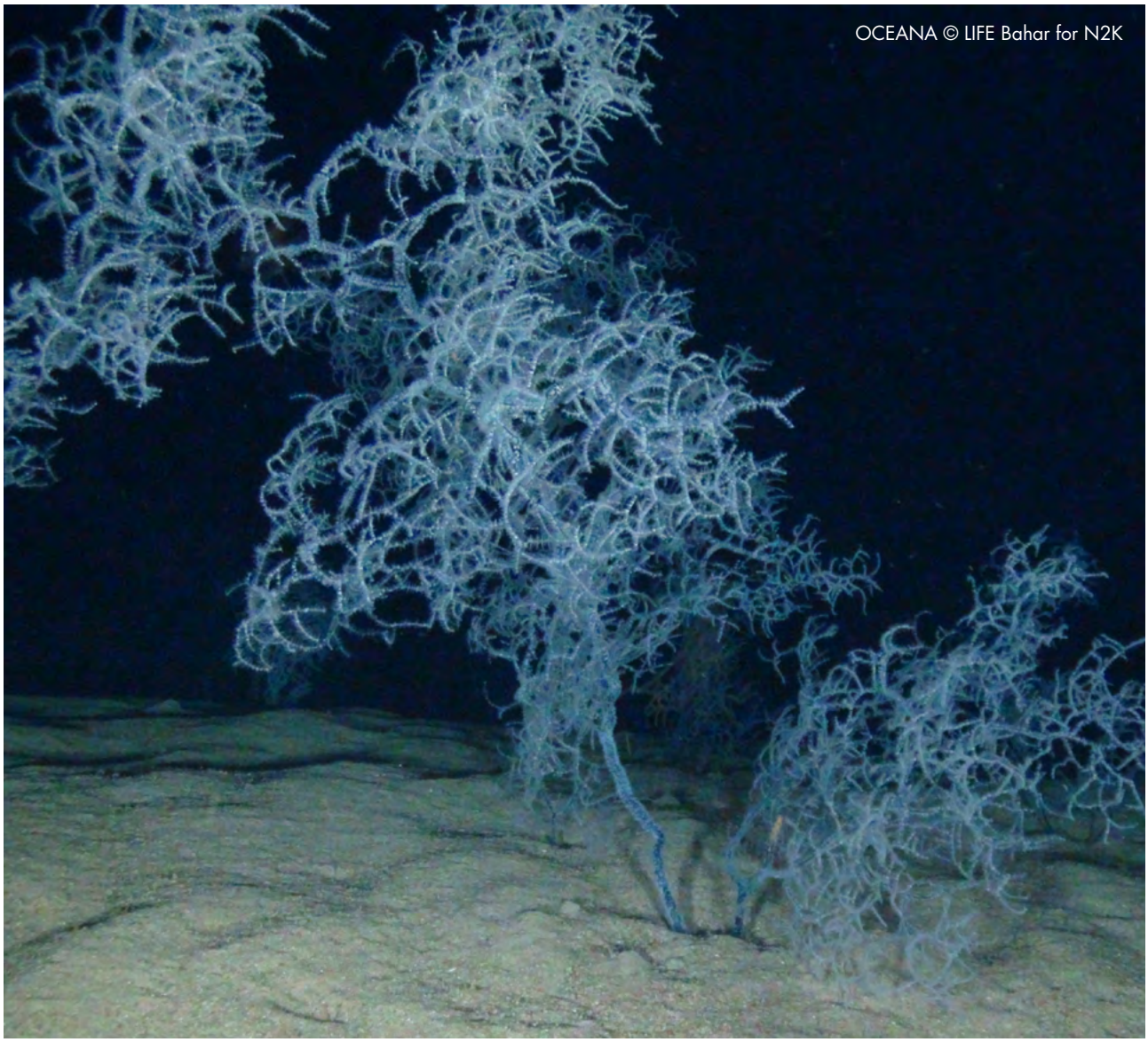
**UNGA (United Nations General Assembly):** The principal policy-making organ of the United Nations, which has adopted key resolutions on sustainable fisheries and protection of VMEs in the high seas.

**VME (Vulnerable marine ecosystem):** Groups of species, communities, or habitats that may be vulnerable to impacts from fishing activities.

**VMS (Vessel monitoring system):** A satellite-based tracking system that transmits vessel position data to fisheries authorities to monitor fishing activity and ensure compliance with spatial and regulatory measures.

# Scope of the report

This report provides a concise synthesis of current scientific knowledge on the ecological and climate-related importance of Mediterranean deep-sea ecosystems and the need to protect them from bottom-contact fishing. The study reviews the role of deep-sea (600-1000 m) habitats as biodiversity hotspots, essential fish habitats, and potential climate refugia, examining how their stable environmental conditions may buffer species against climate change impacts. It assesses the effects of bottom-contact fishing gears on deep-sea biodiversity, ecosystem functioning, and carbon sequestration, including sediment resuspension and associated biogeochemical consequences. The report also summarises available evidence on the contribution of deep-sea ecosystems to long-term carbon storage and climate mitigation and provides a comparative overview of best conservation practices adopted by regional fisheries management organizations (RFMOs). The findings are intended to support Mediterranean and European decision-makers in evaluating the benefits of strengthened deep-sea protection measures.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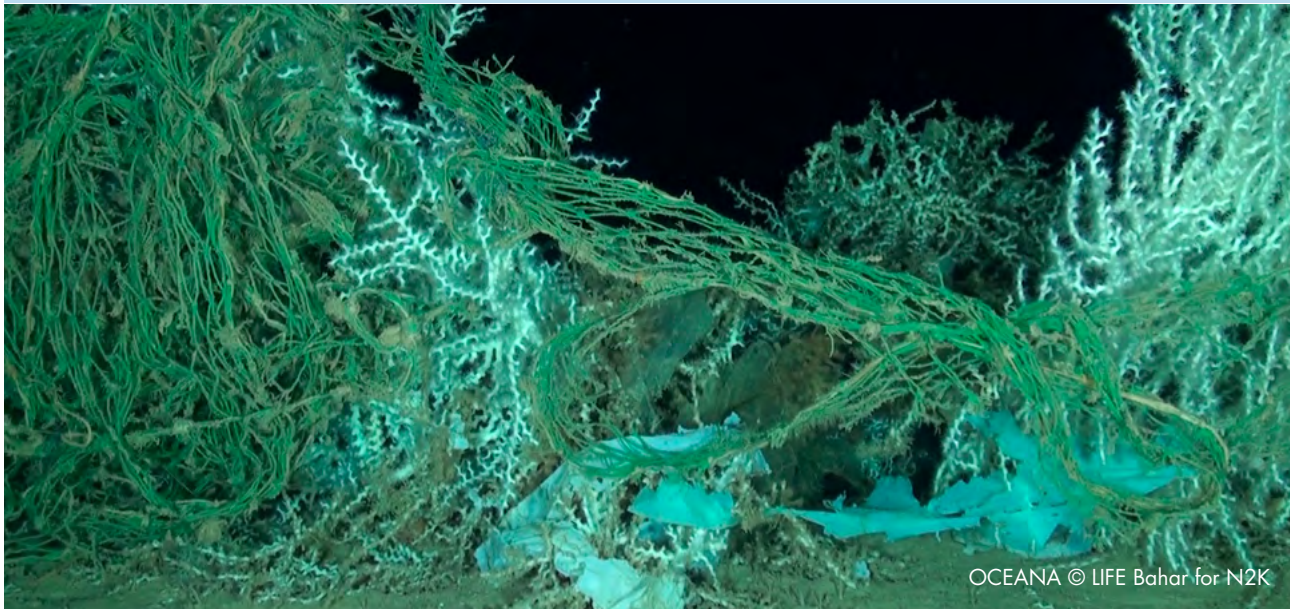
# 1. Ecological Importance of Mediterranean Deep-Sea Ecosystems

## 1.1 The deep sea

The deep sea is defined as the seafloor and water column below approximately 200 m depth (Herring, 2002). For the purposes of this report, the focus is primarily on the benthic ecosystems of the bathyal zone – between 600 and 1000 m depth – which represents a critical interface between exploited continental slopes and more remote deep-sea environments. This depth range is of particular importance because it: i) hosts vulnerable marine ecosystems (VMEs, i.e. areas that may be vulnerable to impacts from fishing activities) (FAO, 2009b); ii) is increasingly exposed to fishing pressure (Morato et al., 2006); and iii) remains comparatively stable in terms of temperature and environmental variability (Hartwell et al., 2024).

**Vulnerable marine ecosystem** (VME) is a term adopted by the United Nations General Assembly (UNGA) under Resolution 61/105 in 2006, based on growing concerns about the adverse impacts of fisheries on high seas ecosystems (Auster et al., 2011). In 2009, the FAO developed its International Guidelines for the Management of Deep-sea Fisheries in the High Seas to prevent significant adverse impacts on VMEs while allowing for sustainable fisheries (FAO, 2009a). According to those guidelines, VMEs are identified on the basis of at least one of the following criteria: (i) uniqueness or rarity; (ii) functional significance; (iii) fragility; (iv) life history traits that contribute to slow recovery; and (v) structural complexity. The most vulnerable ecosystems are characterized by both high susceptibility to disturbance and lengthy recovery times, potentially leading to non-recovery. Examples of VMEs include cold-water coral reefs and sponge beds, which rely on habitat-forming species (FAO, 2009a).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# 1.2 Key deep-sea habitats, species, and their ecological importance

Deep-sea habitats represent the largest and least explored biome on Earth, covering more than 60% of the planet's surface and hosting a substantial proportion of global marine biodiversity. Despite historically being considered homogeneous and biologically impoverished, deep-sea environments are now recognized as highly heterogeneous ecosystems characterized by a wide variety of geomorphological structures and biological assemblages (Ramirez-Llodra et al., 2011; Danovaro et al., 2014).

The deep sea is home to a mosaic of habitats, such as submarine canyons, seamounts, cold-water coral reefs, sponge grounds, and extensive bathyal and abyssal soft-sediment plains.

These habitats differ in physical structure, hydrodynamics, and biogeochemical conditions, leading to strong spatial variability in species composition, biomass, and ecosystem functioning (Ramirez-Llodra et al., 2010).

From an ecological perspective, deep-sea habitats play a key role in supporting biodiversity and maintaining ecosystem processes relative to their productivity (Thurber et al., 2014). Indeed, deep-sea ecosystems provide a wide range of ecosystem services, including carbon sequestration, nutrient recycling, regulation of biogeochemical cycles, and support of fisheries by providing habitats that are essential for the life cycles of commercially important species (Armstrong et al. 2012; Thurber et al., 2014; Pham et al., 2015), such as blackbelly rosefish (*Helicolenus dactylopterus*), blackspot seabream (*Pagellus bogaraveo*), and conger (*Conger conger*). Deep-sea benthic communities play a key role in long-term carbon storage by facilitating the burial of organic matter in marine sediments and regulating benthic respiration processes (Ruhl et al., 2014). Further, carbonate skeletons produced by deep-sea benthic organisms, such as hard corals, some soft corals, and calcareous sponges, represent a form of inorganic carbon storage (Greiffenhagen et al., 2025). Although this process differs chemically from organic carbon burial, it also contributes to long-term carbon sequestration. Biogenic carbonates incorporate dissolved inorganic carbon from seawater into calcium carbonate structures that can persist for centuries to millennia in the deep sea (Reijmer, 2021).
Cold-water coral reefs, for example, form three-dimensional frameworks that accumulate large quantities of calcium carbonate and can act as long-term carbon reservoirs (Oevelen et al., 2009). However, unlike organic carbon burial, carbonate formation releases carbon dioxide during calcification, meaning the net effect on carbon sequestration depends on local alkalinity, dissolution rates, and burial efficiency (Lindberg and Mienert, 2005). Despite this complexity, the long residence time of deep-sea carbonate structures and their eventual burial in sediments means they can indeed be considered a geological carbon sink, albeit one whose efficiency varies across systems and is generally lower than that of organic carbon burial (Titschack et al., 2016).

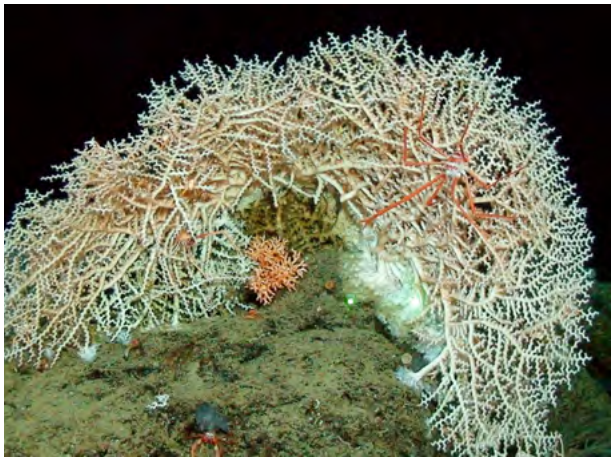
Many deep-sea ecosystems act as biodiversity hotspots, hosting unique and endemic species, as well as supporting complex trophic interactions that link benthic and pelagic domains (Ramirez-Llodra et al., 2010). Structural habitats such as coral reefs, sponge aggregations, and canyon walls enhance habitat complexity and create ecological niches that sustain high levels of secondary production.

Deep-sea habitats are characterized by low resilience and high vulnerability to disturbance. Most deep-sea species exhibit slow growth rates, low reproductive output, and long lifespans, making recovery from physical impacts extremely slow or even impossible on human time scales (Roberts et al., 2006; Danovaro et al., 2014).

## 1.2.1 Cold-water coral ecosystems

Cold-water corals (CWCs) are habitat-forming hard corals that live in deep and cold waters, typically between 200 and 2000 m depth, in aphotic conditions and without symbiotic algae. Unlike tropical corals, CWCs rely entirely on the availability of suspended organic particles and zooplankton (Freiwald et al., 2004; Roberts et al., 2006). They are widely distributed along continental margins, seamounts, ridges, and submarine canyons, where suitable hydrodynamic conditions enhance food supply and facilitate coral growth (Davies and Guinotte, 2011). In general, CWCs are commonly associated with areas characterized by strong bottom currents, abundant sinking organic material, and relatively stable temperature and oxygen conditions (Davies et al., 2008).

Cold-water corals form reefs, complex three-dimensional carbonate structures that significantly increase seafloor heterogeneity. Through their physical frameworks, CWC species act as ecosystem engineers, providing shelter, feeding areas, and nursery habitats for a wide range of associated fauna, including crustaceans, molluscs, echinoderms, polychaetes, and demersal fishes (Henry and Roberts, 2007; Buhl-Mortensen et al., 2010). As a result, CWC reefs are considered biodiversity hotspots in the deep sea, supporting substantially higher species richness and biomass than in surrounding soft-bottom habitats (Roberts et al., 2009).



CWC ecosystems are also characterised by low resilience. The dominant coral species are long-lived, slow-growing, and late-maturing organisms, with growth rates typically ranging from a few millimetres to a few centimetres per year (Lartaud et al., 2019). Individual colonies may reach ages of several decades to centuries, making these habitats extremely vulnerable to physical disturbance and environmental change (Roberts et al., 2006; Orejas et al., 2011; Larsson et al., 2013).

In the Mediterranean Sea, cold-water coral ecosystems are mainly dominated by the hard species *Madrepora oculata* **(Figure 1)** and *Desmophyllum pertusum* (formerly known as *Lophelia pertusa*) (Addamo et al., 2016). These two species are the main reef-forming corals in the Mediterranean basin (Freiwald et al., 2009; Taviani et al., 2011), together with *Desmophyllum dianthus* (Chimienti et al., 2019; Rueda et al., 2019).
This species has been often described as forming solitary polyps, but it can also form dense aggregations of pseudo-colonies (Försterra and Häussermann, 2003). Recent decades have seen a marked expansion in deep-sea habitat research (Skropeta, 2008; Gori et al., 2018; Chimienti et al., 2019) leading to the confirmation of seven Mediterranean CWC provinces (areas with high concentrations of CWCs), between approximately 300 m and 1000 m depth: Bari Canyon (Southern Adriatic Sea); Santa Maria di Leuca (Ionian Sea); South Malta (Strait of Sicily); the Cabliers Coral Mound (Eastern Alboran Sea); the Gulf of Lion, including the Cassidaigne and Lacaze-Duthiers canyons (Western Mediterranean); the Capo Spartivento canyon system, off the southern coast of Sardinia (Western Mediterranean) (Freiwald et al., 2009; Taviani et al., 2017; Chimienti et al., 2019; Lo Iacono et al., 2014); and more recently, the Eastern Ligurian Sea (Fanelli et al., 2017; Bo et al., 2023).

**Figure 1.** Colonies of *Madrepora oculata* (Source: NOAA).

## 1.2.2 Submarine canyons and seamounts

Submarine canyons represent key habitats in deep-sea ecosystems (Fanelli et al., 2018). They are steep, often deeply incised valleys that cut across continental shelves and slopes, connecting shallow coastal environments with deep basins. Canyons are characterized by complex topography, intense water movement, and enhanced sediment transport processes. They act as major conduits for the downslope transport of organic matter, sediments, and nutrients from productive coastal areas to deeper environments, thereby enhancing benthic–pelagic coupling and local biological productivity (Canals et al., 2006; Masiá et al., 2024). Canyons are recognized as biodiversity and biomass hotspots within the deep sea. Their varied substrates provide suitable conditions for the settlement of sessile suspension feeders such as cold-water corals, sponges, gorgonians and bryozoans, while sediments often host dense assemblages of deposit-feeding and scavenging fauna (De Leo et al., 2010; Fernandez-Arcaya et al., 2017). Submarine canyons also play a fundamental role in structuring deep-sea food webs, facilitating the transfer of organic matter and nutrients laterally and across depths, supporting complex trophic networks linking planktonic and benthic compartments (De Leo et al., 2010; Danovaro et al., 2014). These processes make canyons essential habitats for many commercially important fish and invertebrate species.

The Mediterranean Sea hosts one of the highest densities of submarine canyons in the world, with over 500 canyons distributed along its continental margins (Harris and Whiteway, 2011; Fanelli et al., 2018). In the Mediterranean Sea, submarine canyons such as the Blanes, Palamós, Lacaze-Duthiers, Cassidaigne, and Bari canyons support particularly rich benthic and benthopelagic communities. At the same time as Mediterranean canyons represent essential fish habitats for commercial species such as European hake (*M. merluccius*), red shrimps (*Aristaeomorpha foliacea* and *Aristeus antennatus*), and Norway lobster (*Nephrops norvegicus*) (D'Onghia et al., 2012), they are also preferential targets for bottom trawling and other fishing activities, leading to habitat degradation, resuspension of sediments, and direct damage to benthic communities (Ramirez-Llodra et al., 2011; Puig et al., 2012). In addition, canyons often act as sinks for marine litter and contaminants, further threatening their ecological integrity (Pham et al., 2014b).

Seamounts are prominent submarine elevations, typically of volcanic origin, that rise hundreds to thousands of metres above the surrounding seafloor and are among the most widespread geomorphological features of the global ocean (Clark et al., 2010). Their steep flanks and summit plateaus strongly modify local hydrodynamics, generating intensified currents, internal waves, and vertical mixing that enhance the movement of nutrients in otherwise nutrient-poor deep-sea environments (Clark et al., 2010). These physical processes promote nutrient retention, particle trapping, and the flow of organic matter between the seafloor and overlying waters (known as benthic–pelagic coupling), ultimately sustaining elevated primary and secondary productivity. As a result, seamounts often function as ecological hotspots, supporting diverse benthic and pelagic assemblages, including long-lived, habitat-forming species, migratory fishes, and top predators (Würtz & Rovere, 2015). In the Mediterranean Sea, more than 200 seamount-like features have been identified, although only a fraction has been formally mapped and biologically surveyed. Key such structures include the Eratosthenes Seamount, Vavilov and Marsili seamounts, the Adventure Bank, the Emile Baudot seamount, and numerous smaller elevations across the Tyrrhenian (e.g. **Figure 2**), Ionian, and Levantine basins. These features frequently host VMEs, including cold-water corals, sponge grounds, and other habitat-forming taxa dominated by slow-growing, long-lived species (Clark et al., 2016; Würtz & Rovere, 2015; Williams et al., 2010).

As such, Mediterranean seamounts are critical biodiversity reservoirs. At the same time, they are also highly sensitive to disturbance from fishing and other human activities.

Given their ecological significance and vulnerability, submarine canyons and seamounts are increasingly recognized as priority areas for deep-sea conservation and management and are frequently proposed as candidates for marine protected areas (MPAs) and other spatial protection measures in marine policies (Fernandez-Arcaya et al., 2017; Morato et al., 2018; Fanelli et al., 2021).

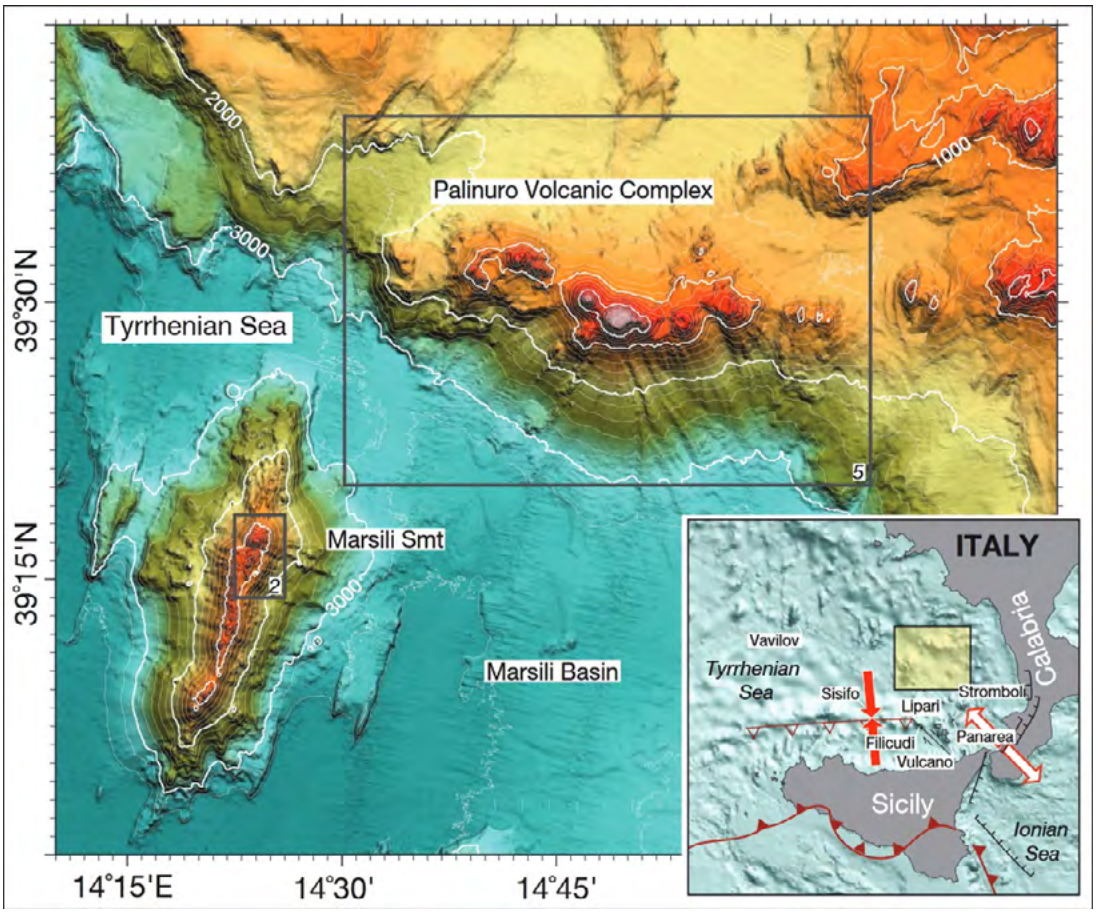



**Figure 2.** Bathymetry of the southern Tyrrhenian Sea. The inset shows a schematic representation of the tectonics affecting southern Italy. (M. Ligi et al., 2014)

## 1.2.3 Sponge grounds

Sponge grounds are deep-sea habitats dominated by high densities of large demosponges and glass sponges (hexactinellids). These habitats are widely distributed across continental margins, seamounts, and submarine canyons, typically at depths ranging from 200 m to over 1500 m (Maldonado et al., 2017). Deep-sea sponges act as important ecosystem engineers by creating shelter, feeding surfaces, and settlement substrates for a wide range of associated organisms, including crustaceans, polychaetes, echinoderms, bryozoans, and juvenile fishes (Buhl-Mortensen et al., 2010; Beazley et al., 2013). As a result, sponge grounds are recognised as biodiversity hotspots. From a functional perspective, sponges play a crucial role in biogeochemical cycling, converting particulate organic matter and dissolved organic carbon into particulate detritus available to other benthic organisms (Hanz et al., 2022). This process, known as

the "sponge loop", enhances organic matter retention and supports the growth of other organisms that feed on this detritus (known as secondary production) in deep-sea ecosystems (de Goeij et al., 2013; Maldonado et al., 2012). Like other deep-sea species, they can only tolerate a limited range of environmental conditions and have low dispersal capability, which limits their adaptive potential to climate change, and their slow growth rates and long lifespans may hinder their capability to recover after disturbances (Levin et al., 2019).

In the Mediterranean Sea, sponge grounds dominated by large demosponges (e.g., *Geodia* spp., *Pachastrella* spp., *Poecillastra* spp.) (Bo et al., 2012; Enrichetti et al., 2020) are often associated with cold-water coral reefs and submarine canyons, where suitable hydrodynamic conditions, mixing of different water masses (Kazanidis et al., 2019), and the presence of hard substrates promote the development of dense sponge assemblages.

## 1.2.4 Bathyal soft-sediment plains

Bathyal soft-sediment plains represent the most extensive habitat type in deep-sea ecosystems, covering vast areas of continental slopes and deep basins. These habitats are characterized by fine-grained sediments, low hydrodynamic energy, and relatively homogeneous physical structure, typically occurring at depths of between 200 m and 4000 m (Danovaro et al., 2020). Although often perceived as biologically uniform, soft-sediment plains host diverse assemblages of organisms that live on and within the seabed, including soft corals (Alcyonacea), polychaetes, crustaceans, echinoderms, molluscs, and foraminifera. These communities play a fundamental role in ecosystem functioning by regulating organic matter degradation and nutrient recycling, and benthic respiration processes (Levin et al., 2001; Danovaro et al., 2008). Soft-sediment benthic communities are primarily supported by organic matter that falls from surface waters. The quantity and quality of this material decrease with depth and distance from productive coastal areas, leading to strong gradients in biomass, diversity, and trophic structure across different depths and regions (Rex and Etter, 2010). Benthic organisms contribute to the burial of organic carbon through bioturbation and sediment mixing, thereby regulating the efficiency of carbon storage in marine sediments and influencing global biogeochemical cycles (Danovaro et al., 2008b; Thurber et al., 2014).

In the Mediterranean Sea, bathyal soft-sediment habitats support diverse megafaunal assemblages dominated by echinoderms, decapod crustaceans, and demersal fishes, including species of high commercial value such as European hake (*Merluccius merluccius*), blackbelly rosefish (*Helicolenus dactylopterus*), red shrimps (*Aristaeomorpha foliacea* and *Aristeus antennatus*), rose shrimp (*Parapenaeus longirostris*), and Norway lobster (*Nephrops norvegicus*). These habitats represent the background matrix within which structurally complex systems such as canyons, coral reefs, and sponge grounds are embedded. Despite their apparent resilience, bathyal soft-sediment ecosystems are increasingly exposed to anthropogenic pressures, including bottom trawling (Ramirez-Llodra et al., 2011; Levin et al., 2019).

## 1.2.5 Sea pen fields

Sea pens (Octocorallia: Pennatulacea) are soft-bottom octocorals that anchor in muddy or sandy sediments using a muscular peduncle (Williams, 2011). Unlike sessile fauna that require hard substrata, sea pens can occupy extensive soft-sediment areas (Williams, 1992). When present at sufficient densities, they can form three-dimensional habitats that enhance local biodiversity, providing shelter and nurseries for invertebrates and fish, including serving as larval habitat (Baillon et al., 2012; Boulard et al., 2024). They also influence near-bottom flow, enhancing retention of organic matter (Eckman, 1985; Cerrano et al., 2010). Sea pens are characterized by slow growth and long lifespans (Wilson et al., 2002), which makes them slow to recover from bottom-contact fishing (Heifetz et al., 2009; Malecha & Stone, 2009). Several sea pen species occur on Mediterranean bathyal soft sediments, with *Funiculina quadrangularis* usually the most abundant (Lauria et al., 2017). Other sea pens present in the area are *Kophobelemnon stelliferum, K. leucharti, Pennatula rubra, P. aculeata, P. phosphorea, Pteroeides spinosum, P. griseum, Veretillum cynomorium, Cavernularia pusilla, Kophobelemnon leucharti, K. stelliferum, Crassophyllum thessalonicae, Protoptilum carpenterii* and *Virgularia mirabilis* (Bastari et al., 2018).

## 1.2.6 *Isidella elongata* fields

The bamboo coral *Isidella elongata* (Esper, 1788) is a candelabrum-shaped octooral (**Figure 3**) a key component of deep Mediterranean ecosystems. It is distributed throughout the Mediterranean Sea and adjacent Gulf of Cadiz and north-western Moroccan waters (Cartes et al., 2013). It occurs between 115 m and 1656 m depth, mainly on bathyal soft bottoms below 500 m, where it forms characteristic aggregations (Lauria et al., 2017). Colonies rarely exceed 80 cm in height.

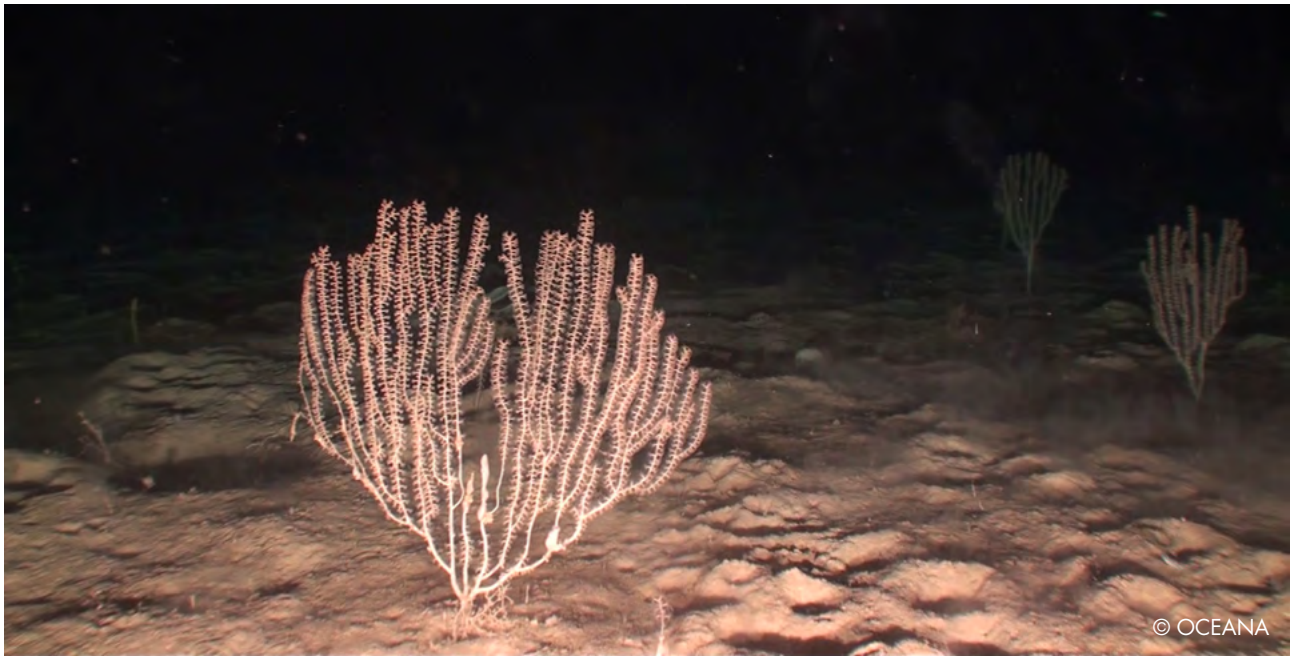
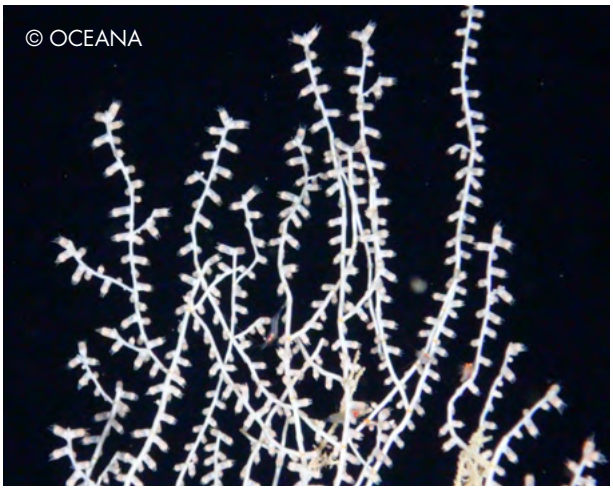



**Figure 3.** *Isidella elongata* fields (© OCEANA)

As a habitat-forming species, *I. elongata* creates structurally complex aggregations that enhance habitat heterogeneity and provide substrata for epibionts (Mastrototaro et al., 2017). These aggregations function as feeding, spawning, and nursery areas for species such as long-finned squid (*Loligo forbesii*) and blackmouth catshark (*Galeus melastomus*). They also support commercially valuable crustaceans (*A. antennatus, A. foliacea, P. longirostris, N. norvegicus*) and demersal fishes like European hake(*M. merluccius*), blue whiting (*Micromesistius poutassou*), greater forkbeard (*P. blennoides*), four-spot megrim (*Lepidorhombus boscii*), blackbelly rosefish (*H. dactylopterus*), which are often larger and more abundant within these habitats (Mytileneou et al., 2014).

As *Isidella elongata* aggregations are distributed on soft bottoms, they are highly vulnerable to deep-sea fisheries. Bottom trawling causes colony removal and breakage (Carbonara et al., 2020), and the species, once widespread, is now restricted to scattered, low-density populations, having disappeared from several heavily trawled areas. Slow growth, longevity (up to approximately 400 years) and limited dispersal mean that the resilience of *I. elongata* is very low (Andrews et al., 2009). Consequently, *it* is listed as "Critically Endangered" in the Mediterranean by the IUCN and recognised as a vulnerable deep-water habitat under regional and EU conservation frameworks (Otero et al., 2017).




## 1.2.7 Other deep-sea habitats

Cold seeps and hydrothermal vents in the Mediterranean Sea represent localized hotspots of marine life, sustaining biological communities that are fuelled by energy derived from microbial digestion of chemicals such as methane and hydrogen sulphide (known as 'chemosynthesis'), rather than photosynthetically derived carbon (Ramirez-Llodra et al., 2010; Ritt et al., 2010). Cold seeps are widely distributed along Mediterranean continental margins, accretionary prisms, and deep basins, including the Eastern Mediterranean mud volcano provinces and the Nile deep-sea fan (Olu-Le Roy et al., 2004; Ritt et al., 2010). Although Mediterranean hydrothermal vents are generally characterized by lower temperatures and fluid fluxes than mid-ocean ridge systems, vent fields in the Aegean and Tyrrhenian regions host diverse microbial assemblages and specialized fauna (Kiel, 2016).

Both seeps and vents play a key role in benthic–pelagic coupling and carbon cycling, acting as biogeochemical filters that regulate methane and sulphide fluxes through chemical processes such as anaerobic oxidation (Boetius and Wenzhöfer, 2013). Despite their ecological importance, Mediterranean chemosynthetic ecosystems are highly vulnerable to physical disturbance and environmental change, as they are often dominated by slow-growing, endemic species with limited dispersal, raising concerns about their resilience under increasing anthropogenic pressure (Suzuki et al., 2018). Both cold seeps and hydrothermal vents are classified as VMEs (FAO, 2009).

# 2. Impacts of Mediterranean Fisheries on Deep-Sea Ecosystems

## 2.1 Bottom-contacting gears and biodiversity impacts

Bottom trawling is globally recognized as one of the most destructive human activities, with severe environmental impacts affecting the seabed and associated ecosystems (Eigaard et al., 2017; Sciberras et al., 2018). The repeated and poorly regulated use of non-selective bottom-contact fishing gears represents a major driver of seabed homogenization and biodiversity loss, reducing habitat complexity and altering benthic community structure, with long-lasting consequences for ecosystem functioning and resilience (Clark et al., 2016; Hiddink et al., 2017; Sciberras et al., 2018; Paradis et al., 2021).

Research has shown that the chronic trawling activity may result in slower recovery times, especially in deep-sea areas characterised by slow-growth species. Deep mobile trawl gears – characterised by heavy doors weighing 2-5 tonnes each and sometimes more, and nets of about 25 m width (Clark et al., 2016) – cause the direct removal of bioengineering species and sediment resuspension, thus altering natural sediment fluxes, as documented for Mediterranean canyon systems (Pusceddu et al., 2014; Hiddink et al., 2017; Clark et al., 2019; Maiorano et al., 2022; Puig et al., 2012). Additionally, static gears such as bottom longlines and traps, even if considered less impacting than mobile gears in certain conditions, can cause the breakage of sessile fauna such as sponges and corals during the retrieval process (Fosså et al., 2002; Sampaio et al., 2012; Ewing and Kilpatrick 2014; Pham et al., 2014a).

The impacts of bottom-contacting gears are pronounced in the Mediterranean Sea, where bottom trawling is one of the most widespread anthropogenic disturbances (Agnetta et al., 2025; Marguin et al., 2025). Long-term assessments of the impacts of chronic trawling pressure in the Mediterranean have documented reductions in biodiversity and functional resilience (Hiddink et al., 2017), highly impacting vulnerable species and reshaping food-web interactions and ecosystem functioning (Pusceddu et al., 2014; Farriols et al., 2017; Agnetta et al., 2025).

## 2.2 Impacts of bottom-contacting gears on ecosystem stability and carbon sequestration

Among the wide range of ecosystem services provided by the deep sea (Armstrong et al., 2012), carbon storage and long-term carbon sequestration stand out as two of its most critical functions (Armstrong et al., 2012; Thurber et al., 2014). These processes make deep-sea ecosystems a key component of the global carbon cycle and an important natural carbon sink (Arndt et al., 2025; Veselić et al., 2025). Recent assessments further show that continental margin sediments constitute one of Earth's largest and most persistent long-term carbon sinks, where the burial of organic carbon helps regulate atmospheric carbon dioxide levels and modulates ocean–atmosphere carbon exchange (Arndt et al., 2025).

Beyond sedimentary processes, the stability and overall functioning of deep-sea ecosystems

also depend on the presence of assemblages of habitat-forming species such as sponges, corals, bryozoans, and ascidians (Rossi, 2013; Thurber et al., 2014; Cau et al., 2021). Such species increase structural complexity, promote particle capture and nutrient processing, and act as additional long-term carbon sinks within bathyal habitats (Gili and Coma, 1998). In these environments, trawling tends to produce more severe and persistent damage than in shallow waters, as deep-sea benthic communities are generally less resilient, and more vulnerable to physical disturbance (Rijnsdorp et al., 2018). The mechanical impacts of trawl gear remove biogenic habitats such as animal forests, reducing three-dimensional complexity and eliminating long-lived suspension feeders that sustain benthic food webs and productivity (Watling and Norse, 2009). As these structural organisms disappear, food webs structure become simplified and are increasingly dominated by opportunistic species with limited functional contributions (Pusceddu et al., 2014).

In addition to habitat degradation, bottom trawling generates intense sediment resuspension, fostering the formation of turbidity plumes. Studies in the southwestern Mediterranean Sea have found that periods of trawling activity coincide with increased turbidity and suspended sediment concentrations, showing sediment transfer into the water column and downward transport into deeper layers (Arjona-Camas et al., 2024). Sediment plumes can extend tens of kilometres beyond fishing grounds (Payo-Payo et al., 2017), disrupting sediment-water exchanges at the seafloor and releasing regenerated nutrients into the water column. These nutrients may stimulate pelagic primary production in adjacent areas and modify the physical and biogeochemical conditions of the water column (Pusceddu et al., 2005; Bradshaw et al., 2012; Arjona-Camas et al., 2024).

Other key ecosystem services arise within deep-sea soft-sediment habitats, where essential functions include the biogeochemical processes that drive the decomposition of organic matter and nutrient cycling (Olsgard et al., 2008). In these habitats, physical disturbance from bottom-contacting gears reduces the abundance of key bioturbating species that normally oxygenate sediments, regulate nutrient flows, and support key linkages between the seafloor and the water column, by reworking sediment and irrigating burrows[1] (Hiddink et al., 2007). As a result, the observed changes in ammonium, nitrate, and silicate show that trawling has altered the processes controlling how nutrients are regenerated in sediments and transferred across the sediment–water interface.

Consequently, nutrient regeneration becomes less efficient and the functional capacity of the benthic system declines (Norling et al., 2007). Increased sediment resuspension accelerates the remineralization of organic matter and reduces the efficiency of long-term carbon burial, leading to substantial losses of sedimentary organic carbon and slower turnover rates in chronically trawled areas (Pusceddu et al., 2014). The combined depletion of labile carbon pools and the greater exposure of sediments to oxygen weaken the role of deep-sea sediments as long-term carbon sinks and contribute to broader changes in nutrient cycling (Pusceddu et al., 2005; Payo-Payo et al., 2015).

Recent global assessments further demonstrate that bottom trawling undermines the long-term ability of marine sediments to store carbon, by stirring up and breaking down organic matter that was previously buried (Zhang et al., 2024). This process releases substantial amounts of carbon dioxide back into the water column (Hiddink et al., 2023), some of which may ultimately re-enter the atmosphere.

[1] Burrow irrigation or bioirrigation, refers to the active or passive transport of overlying water into the burrow systems of infaunal organisms (invertebrates living within seafloor sediments, such as worms, crustaceans, and bivalves)

## 2.3 Evidence from the Mediterranean Sea

Recent analyses of trawling activity in the Mediterranean Sea (Marsaglia et al., 2025) highlight the urgent need to strengthen conservation measures in deep-sea ecosystems. Seafloor mapping across the western and central Mediterranean has revealed persistent trawl marks on continental slopes and submarine canyons, demonstrating long-term physical alteration of deep-sea sediments (Puig et al., 2012).

In the Blanes Canyon system, repeated trawling has eroded surface layers, deepened the sediment mixed layer, and accelerated downslope sediment transport, reshaping canyon morphology (Martín et al., 2014). Similar patterns of chronic erosion and sediment displacement have been documented along the Ebro margin, where trawl scars persist due to extremely low natural sedimentation rates (Palanques et al., 2014). These geomorphological impacts confirm that such deep-sea habitats in the Mediterranean are unable to recover between trawling events (Ramirez-Llodra et al., 2011).

Deep-sea coral and sponge grounds in the Santa Maria di Leuca province exhibit extensive damage and reduced structural complexity in areas exposed to trawling (D'Onghia et al., 2012). Trophic studies in the Balearic basin further reveal declines in megafaunal biomass and altered food-web structure in trawled canyon systems (Fanelli et al., 2013a, b). These patterns mirror broader evidence that bottom trawling disproportionately affects slow-growing Mediterranean deep-sea species with limited resilience (Thrush & Dayton, 2002; Hiddink et al., 2026). Taken together, regional case studies demonstrate that bottom trawling undermines biodiversity conservation, ecosystem functioning and the carbon sequestration capacity of Mediterranean deep-sea habitats, highlighting their high sensitivity to cumulative anthropogenic pressures (Ramirez-Llodra et al., 2011).

## 2.4 Other industrial pressures

Beyond the direct effects of bottom trawling, deep-sea ecosystems are increasingly exposed to multiple industrial pressures whose cumulative impacts amplify ecological disturbance (Ramirez-Llodra and Banet, 2020; Halpern et al., 2025). Activities such as submarine cable installation, hydrocarbon exploration and production, marine wind farm construction, and emerging deep-sea mining generate seabed destruction and sediment resuspension that add to the effects of trawling (Van Dover, 2011, 2017, 2018; Ramirez-Llodra et al., 2015; Boschen et al., 2016; Levin et al., 2016; Amon et al., 2022). As an example, drilling and mining operations further contribute to habitat smothering, changes in sediment texture, and long-term alterations of benthic biogeochemistry, with recovery timescales often spanning decades (Van Dover 2014a; Ramirez-Llodra et al., 2015; Jones et al., 2016; Gollner et al., 2017; Cuvelier et al., 2018).

In the Mediterranean Sea, large-scale commercial deep-sea mining is not currently planned, and the basin remains largely free from direct mining impacts. However, ongoing technological advancements, increasing demand for critical minerals, and renewed interest in offshore resource exploration may progressively increase the likelihood of deep-sea prospecting (Yao et al., 2025). In this context, the already high cumulative pressure from trawling and other industrial activities reduce ecosystem resilience, potentially lowering the threshold at which future disturbances could trigger irreversible ecological and biogeochemical change.

# 3. Current Knowledge on the Role of Deep-Sea Ecosystems in Climate Change Adaptation and Mitigation

Deep-sea ecosystems play a fundamental role in climate-change mitigation, through multiple, interconnected processes. In the Mediterranean Sea, these processes are particularly relevant because the basin is semi-enclosed, nutrient-poor, and characterised by naturally low sedimentation rates, conditions that enhance the long-term preservation of organic carbon in deep-sea sediments. Low sedimentation rates reduce physical dilution and limit bioturbation, thereby favouring the accumulation and burial of refractory organic matter. Recent studies show that Mediterranean deep-sea sediments efficiently bury carbon compared with the amount of organic material available, highlighting their importance as long-term carbon reservoirs despite the basin's overall low productivity (Paradis et al., 2021; Tesi et al., 2008).

However, growing evidence indicates that anthropogenic disturbance can significantly weaken this climate-regulating function. In the Mediterranean, where deep-sea recovery rates are inherently slow, repeated disturbance may shift sediments from long-term carbon sinks toward net carbon sources, with implications for regional carbon budgets and climate feedback (Martin et al., 2014). These findings highlight the critical but vulnerable role of Mediterranean deep-sea ecosystems in climate change mitigation and emphasize the need for improved monitoring and management of activities affecting the seafloor.

## 3.1 Effects of climate change on deep-sea marine species

A growing body of observational evidence indicates that contemporary climate change is already affecting deep-sea ecosystems. Predicted consequences include rising deep-water temperatures (Purkey & Johnson 2010), with climate velocities accelerating to 11 times the present rate in waters between a depth of 200 and 1000 metres by 2100 (Brito-Morales et al., 2022), widespread deoxygenation by 3.7% or more (Stramma et al., 2008, 2010; Keeling et al., 2010; Helm et al., 2011), decreasing pH in intermediate and deep waters by 0.29-0.37 units (Byrne et al., 2010), and shifts in the flow of particulate organic carbon reaching the seafloor (Smith et al., 2013).

These climate-driven changes can alter growth, survival, and recruitment of deep-sea species, limit natural recovery, and reduce the effectiveness of restoration efforts. Rising temperatures, declining oxygen, and acidifying water may further impair metabolic processes in deep-sea organisms, which are often more sensitive to environmental change than shallow-water species (Fabry et al., 2008). Their resilience will depend on their ability to adapt rapidly and maintain essential biological interactions.

The deep Mediterranean Sea is not exempt from climate change, and the basin is considered a climate change hotspot, which is warming 20% faster than the global average (MedECC 2020). Observational records show that Mediterranean deep waters have been warming steadily over past decades, with rates of approximately +0.002 to +0.004 °C $yr^{-1}$ in the Western Mediterranean Deep Water (WMDW) and +0.001 to +0.002 °C $yr^{-1}$ in the

Eastern Mediterranean Deep Water (EMDW). Climate-model projections indicate that, under high emission scenarios, deep-water temperatures may increase by ~0.5–1.5 °C by 2100, depending on the basin, depth, and scenario (Kubin et al., 2023; Schreder et al., 2016; Sannino et al., 2022). Although this increase may appear small, it represents a huge variation in a relatively stable environment that is characterised by very small variations in temperature across seasons and years. Here, long-term changes in the trophic level of deep-sea species were reported (Fanelli et al., 2016), suggesting a widespread shift in the food web. This decline in trophic level is linked to warming deep waters, decreased oxygen levels, and reduced food availability, causing organisms to shift to smaller or more pelagic prey and thus lowering their trophic position.

Climate change affects sessile species more severely. VME indicator taxa can be adversely affected by both short-term and long-lasting disturbances, arising also from climate-related stressors (Gammon et al., 2018; Levin et al., 2019; Ramirez-Llodra et al., 2011; Sweetman et al., 2017). Shifts in environmental conditions, including altered temperature patterns (NOAA, 2019), changes in seawater pH (Sabine et al., 2004; Smith et al., 2008), variations in the quality and availability of particulate organic carbon (Levin et al., 2019), and declining oxygen concentrations (Keeling et al., 2010; Stramma et al., 2010) are expected to influence the physiological and metabolic functioning of these species (Dodds et al., 2007).

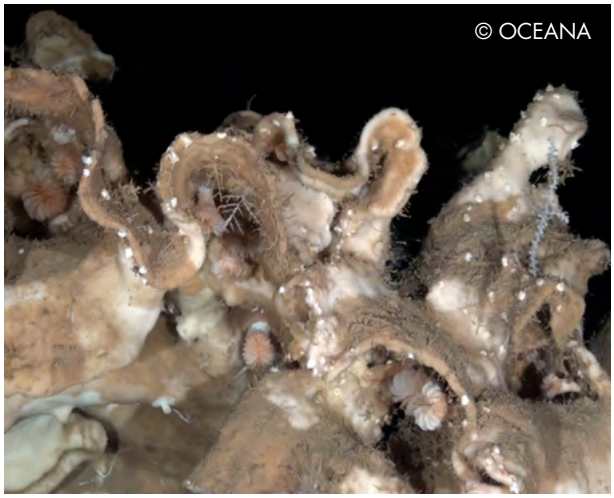
Fish communities are also affected by climate change in the Mediterranean Sea. A recent study identified a significant increase in the Mean Temperature of the Catch (MTC) and a shift in fish community composition, with a trend towards an increase of warmer water species and a northward shift (the so-called "poleward migration") of temperate species (Valente et al., 2025). Deep-sea fish communities on the continental slope (>200 m depth) showed the slowest shifts in species composition in response to warming. Although their MTC increased only marginally, 0.004 °C per year, these communities remain highly vulnerable due to a marked "under-adaptation", meaning their thermal responses lag the rapid rise in bottom temperatures. A northward shift in distribution density is also foreseen for different species in the Adriatic basin (Panzeri et al., 2024) suggesting potential similar responses in other Mediterranean regions.

## 3.2 Biological and ecological characteristics supporting resilience to climate impacts

Deep-sea species possess many biological and ecological characteristics that can enhance their resilience to climate-driven change, even though these environments are increasingly exposed to warming, deoxygenation, acidification, and declining food supply. Many deep-sea organisms have extremely slow metabolisms and long lifespans, traits that reduce their energetic demands and allow them to persist through prolonged periods of environmental stress (Seibel et al., 2007). These slow life histories, while often associated with vulnerability to disturbance, can also buffer populations against short-term fluctuations in temperature or food availability (Danovaro et al., 2017). In some regions, such as the Mediterranean deep sea or areas influenced by hydrothermal activity, species have evolved broader physiological tolerances, including enhanced thermal resistance, which may partially protect against moderate warming (Naumann et al., 2014; Company et al., 2008).

Dietary flexibility is another important factor that can enhance resilience. Many deep-sea organisms are opportunistic feeders capable of exploiting a wide range of food sources,

from sinking particulate organic matter to carrion and microbial production (Fanelli et al., 2013). This trophic versatility can help species cope with shifts in the quantity or quality of surface-derived food, a key consequence of climate-driven changes in primary productivity (Smith et al., 2009). Reproductive strategies also play a role: some species produce large, energy-rich eggs or larvae that can sustain longer development and dispersal phases, increasing larval survival during transport and thereby enhancing genetic connectivity among populations (Baco et al., 2016; Viegas et al., 2024).




At the ecosystem level, habitat heterogeneity contributes significantly to resilience. Features such as canyons, seamounts, cold seeps, and vent fields create mosaics of microhabitats that can act as climate refugia, allowing species to shift locally rather than migrate long distances (Paulus, 2021). In addition, some deep-sea communities exhibit functional redundancy, meaning that multiple species perform similar ecological roles; this redundancy can help maintain ecosystem functioning even when individual species decline (Levin & Le Bris, 2015). Further, chemosynthetic ecosystems, such as hydrothermal vents and methane seeps, may be less sensitive to changes in surface productivity because their primary production is fuelled by chemical energy rather than sunlight, although they remain vulnerable to temperature and fluid-flow alterations (Levin et al., 2016). However, as in the deep sea, many of these mechanisms operate over long temporal scales, while environmental changes are occurring rapidly. Resilience could therefore be insufficient to counteract the pace of anthropogenic climate impacts. This underscores the need for precautionary management and conservation strategies.

In the Mediterranean Sea, these resilience traits are further shaped by the basin's unusually warm deep waters, which favour higher thermal tolerance but also push many cold-affinity species close to their physiological limits.

Deep-sea ecosystems such as CWC reefs, sponge grounds, and seamount communities play a crucial role in buffering ecological variability by providing structural complexity, stable microhabitats, and refugia for a wide range of species. When these systems remain intact, their three-dimensional frameworks can moderate environmental fluctuations, support diverse assemblages, and maintain essential ecological functions even under changing ocean conditions. However, once degraded – whether by warming, acidification, deoxygenation, or physical disturbance – their capacity to act as climate refugia is severely reduced, as structural collapse and biodiversity loss diminish both habitat availability and functional redundancy (Roberts & Cairns, 2014; Levin & Le Bris, 2015). Emerging evidence shows that restored or recovering deep-sea habitats can regain some resilience to perturbations, including the ability to adapt to ongoing and anticipated environmental change. For instance, experimental studies on cold-water corals such as *D. pertusum* demonstrate that colonies can recover from sublethal stress, maintain physiological plasticity, and even acclimate to moderate shifts in temperature or pH when environmental conditions improve (Hennige et al., 2015). Although restoration in the deep sea remains extremely challenging, these findings suggest that protecting remaining intact habitats and facilitating recovery where possible can enhance ecosystem resilience in the face of accelerating climate impacts (Van Dover et al., 2014b).

# 3.3 Deep-sea ecosystems as potential climate refugia

Marine research has increasingly focused on identifying climate refugia (Anderson et al., 2022; Carter et al., 2020; Chollett et al., 2022; Combes et al., 2021), which are defined as *"areas characterized by low climate velocity and high species richness"* (Brito-Morales et al., 2020). Analyses of past and projected trends in climate-sensitive variables help to identify zones of stability versus change (Ban et al., 2016). Researchers have also outlined criteria (such as long-term buffering, reduced exposure to stressors, and ecological accessibility) to refine the concept for specific taxa, including corals (Kavousi & Keppel, 2018). Deep-sea ecosystems, characterized by stable or low variability conditions (Danovaro et al., 2014), are potentially candidates for hosting climate refugia" both for deep species and upper water pelagic species, as they are less directly affected by warming. Epipelagic species (0-200 m), which have limited horizontal mobility, could shift downward to where mesopelagic (200-1000 m) and bathypelagic (1000-3000 m; **Figure 4**) zones offer greater buffering capacity (Lin et al., 2025). In contrast, bathypelagic and abyssopelagic species are less able to move deeper because the abyss provides minimal thermal offset.

Recent studies have modelled habitat suitability and climate projections for different deep-sea sessile species, such as cold-water corals, bamboo corals, and sea pens. By the year 2100, around 60% of currently suitable areas are expected to disappear, while the expansion of new suitable habitats will not compensate for these losses. This decline is mainly driven by a predicted 1-2 °C increase in bottom temperatures along continental margins (Georges et al. 2024; Sweetman et al., 2017). As the western basin warms to temperatures currently typical of the eastern basin, optimal thermal habitats (below 14 °C) are expected to shift westward (Davies et al. 2011). In contrast, changes in bottom salinity and current speed appear minimal and likely play a minor role. Climate impacts follow a longitudinal gradient, with stronger warming and greater habitat loss in the eastern and central basins, especially between 600 and 1000 m depth, whereas the most consistent climate refugia are projected. Overall, suitable habitats are projected to shift toward deeper waters.

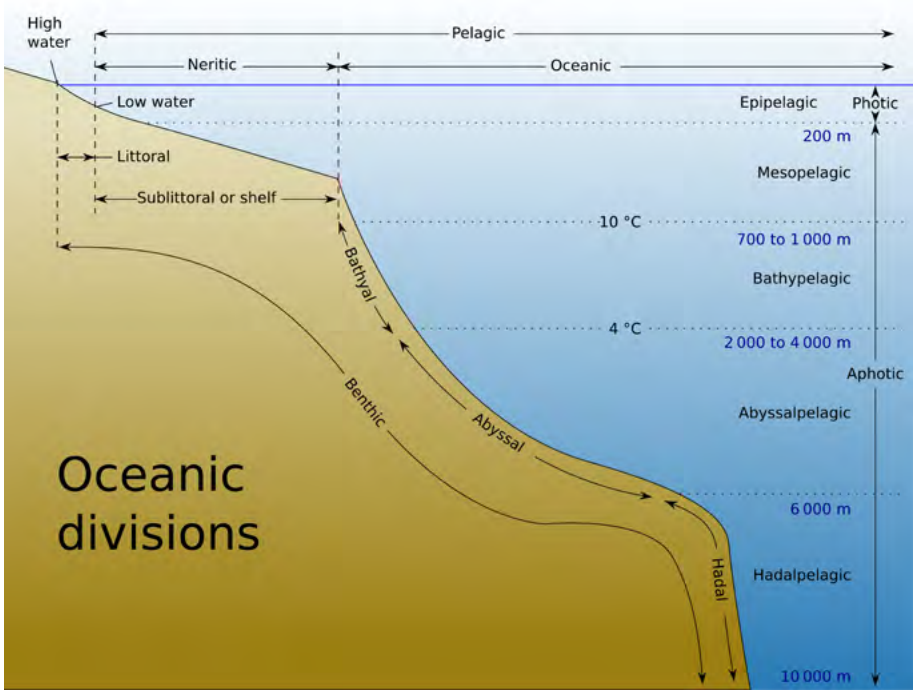



**Figure 4.** Diagram showing the vertical and horizontal divisions of the ocean. It shows how marine environments are structured by depth into pelagic zones (epipelagic, mesopelagic, bathypelagic, abyssal, and hadal) and benthic zones along the seafloor (littoral, sublittoral, bathyal, and abyssal). It also highlights the distinction between photic (sunlit) and aphotic (dark) regions, as well as coastal (neritic) and open-ocean (oceanic) areas. (Source: K. Aainsqatsi).

The loss of deep-sea refugia in biodiversity-rich regions, combined with the physiological limits of deep-sea species and rapidly changing environmental conditions, may further reduce the capacity of deep-sea fauna to cope with ocean warming. As refugia become increasingly compressed and less connected at depth, the opportunities for species to persist, shift, or recolonize suitable habitats decline.

Improved projections of how climate change can lead to shifts in the distribution of deep-sea species is critically important for developing effective management measures that account for such changes. The most relevant such measures are those that aim to preserve refugia areas or local fish stocks, to aid conservation of VMEs, or secure food, income, and livelihoods from fisheries (Bates et al., 2019; Cheung et al., 2017; 2020; Gaines et al., 2018; Thresher et al., 2015; Tittensor et al., 2010). Such improved projections can also inform the designation of Fisheries Restricted Areas and of 'Other Effective Area-based Conservation Measures' (OECMs; IUCN WCPA, 2019). Environmental niche modelling, also known as species distribution modelling, habitat suitability modelling (HSM), or climate envelope modelling, represents a powerful tool for predicting the distribution of species over wide geographic regions and projecting changes under future climate scenarios (Hattab et al., 2014; Hijmans & Graham, 2006; Pearson & Dawson, 2003; Wiens et al., 2009; Gasbarro et al., 2022).

# 4. Best Practices in Deep-Sea Conservation in RFMOs

## 4.1 Broad-scale conservation measures

Several Regional Fisheries Management Organizations (RFMOs) have adopted precautionary, broad-scale measures to reduce the risk of significant adverse impacts on vulnerable marine ecosystems (VMEs), particularly in regions where detailed spatial information on benthic habitats and species distributions remains incomplete. These measures generally fall into three main categories: depth-based closures, gear limitations, and permanent area closures designed to protect VMEs. Each approach is based on the precautionary principle and has been implemented by different RFMOs, with outcomes that vary according to the availability of scientific data, the effectiveness of monitoring and enforcement, and local ecological conditions.

## 4.2 Depth-based closures

Depth-based closures prohibit or restrict the use of bottom-contact fishing gears below a specified depth as a precautionary measure, based on the assumption that deeper habitats are more likely to host long-lived and vulnerable species such as cold-water corals, sponges, and those found in seamount-associated communities (Rogers et al., 2008; FAO, 2009). Depth thresholds (e.g. restrictions below 800 m in the Atlantic Sea, and 1000 m in the Mediterranean Sea) are widely applied because they provide a clear, objective management criterion, particularly in situations where detailed information on benthic habitats and species distributions is limited or unavailable (UNGA, 2006; FAO, 2009a). The FAO International Guidelines for the Management of Deep-sea Fisheries in the High Seas explicitly recognise depth-based restrictions as a pragmatic interim measure for reducing the risk of significant adverse impacts on vulnerable marine ecosystems, particularly in data-poor contexts (FAO, 2009b).

In the Mediterranean Sea, where deep-sea ecosystems are only partially mapped and increasingly exposed to fishing pressure, depth-based measures have been identified as particularly relevant for mitigating cumulative impacts on vulnerable habitats (Tudela & Simard, 2004; Otero & Marín, 2019). Recent policy-oriented assessments further emphasise that extending depth limits on bottom fishing in the Mediterranean represents an effective and precautionary conservation strategy, considering the high vulnerability and extremely slow recovery rates of deep-sea ecosystems in the region (Oceana, 2024).

Several RFMOs and regional jurisdictions have integrated depth-based rules into their bottom-fishing management frameworks through a combination of conservation and management measures and national regulations implemented within their convention areas. Within the European Union, regulatory instruments on deep-sea fisheries have established measures that limit or prohibit bottom trawling below specific depth thresholds, such as a trawl ban below 800 m introduced in the North-east Atlantic, with the explicit objective of safeguarding deep-sea habitats and their associated ecosystem functions (European Union, 2016). Similar depth-based approaches have also been implemented within RFMOs to regulate bottom-fishing activities in areas where

VMEs are known or considered likely to occur (NEAFC, 2014; NAFO, 2019). Ongoing discussions within GFCM concern the possible extension of the current Mediterranean bottom trawl ban from below 1000 m depth to below 800 m depth. Pilot studies presented to the GFCM Scientific Advisory Committee (SAC) in 2024 indicate limited associated socio-economic impacts alongside potential benefits for vulnerable deep-sea ecosystems (see Oceana, 2024).

Depth-based closures are relatively straightforward to communicate, monitor, and enforce using vessel monitoring systems, onboard observer programmes, and port controls, allowing for rapid risk reduction in vulnerable deep-sea environments (FAO, 2009). However, depth represents only a coarse proxy for habitat vulnerability, as VMEs may occur across a wide depth range and depth alone does not reliably predict their distribution (Rogers et al., 2008; Clark et al., 2016). Consequently, depth-based measures are most effective when combined with complementary tools, such as gear restrictions and spatial closures, and when progressively refined through improved habitat mapping and advances in scientific knowledge.

In addition to the protection of VMEs, depth-based closures can have other benefits, such as the safeguarding of carbon sequestration processes, the maintenance of climate refugia, and the enhancement of ecosystem resilience to warming, deoxygenation, and acidification.


## 4.3 Gear limitations

Gear limitations are widely adopted by RFMOs to mitigate physical disturbance to deep-sea benthic habitats by restricting or prohibiting fishing gears that come into direct contact with the seabed, such as bottom trawls, bottom-set gillnets, and dredges (FAO, 2009; Clark et al., 2016). These measures are based on the understanding that the vulnerability of deep-sea ecosystems is driven primarily by the type and intensity of physical disturbance rather than by fishing effort alone, and that bottom-contact gears can cause severe and persistent damage to habitat-forming species with limited recovery capacity (Tudela & Simard, 2004; Rogers et al., 2008).

Several RFMOs have adopted gear-based restrictions as core elements of their VME protection frameworks. The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) has long prohibited bottom trawling within its Convention Area and has imposed strict regulations on the use of bottom-contact gears to safeguard benthic ecosystems (CCAMLR, 2009). Similarly, the South Pacific Regional Fisheries Management Organisation (SPRFMO) has implemented conservation and management measures defining permitted bottom-fishing gears and restricting their use in areas where VMEs are known or likely to occur (SPRFMO, 2019). Gear-specific restrictions also form part of the North-East Atlantic Fisheries Commission (NEAFC) and the Northwest Atlantic Fisheries Organization (NAFO) measures addressing bottom fishing in the North Atlantic (NEAFC, 2014; NAFO, 2019).

Gear limitations can be highly effective when supported by clear gear definitions, robust reporting requirements, and efficient monitoring and enforcement systems (FAO, 2009). However, gear restrictions alone may be insufficient to prevent impacts if fishing effort is displaced into previously unfished areas or if alternative gear types continue to exert pressure on sensitive habitats. Consequently, gear-based measures are most effective when combined with spatial management tools, footprint controls, and adaptive management frameworks (Clark et al., 2016; Otero & Marín, 2019).

## 4.4 Permanent area closures for VMEs

Permanent spatial closures represent one of the most effective tools for the long-term protection of VMEs in deep-sea environments. These measures identify areas where bottom-contact fishing activities are prohibited, either because the presence of VMEs have been confirmed through scientific surveys or because there is a high likelihood of their occurrence based on habitat suitability models, encounter data, or expert judgment (UNGA, 2006; FAO, 2009;).

International policy instruments, including UNGA resolutions on sustainable fisheries, explicitly call on States and RFMOs to close areas where VMEs are known, as well as areas where species-specific density or abundance thresholds of VME indicator taxa trigger precautionary closures (i.e., 30 kg of live coral or 100 kg of sponges incidentally caught during trawl fishing operations in the Northeast Atlantic, https://www.fao.org/in-action/vulnerable-marine-ecosystems/vme-indicators/en/), in order to prevent significant adverse impacts from bottom fishing (UNGA, 2006; UNGA, 2009; FAO, 2009; Clark et al., 2016). However, no such thresholds have yet been defined or adopted for the Mediterranean Sea, even though the need for permanent spatial protection in the Mediterranean has been repeatedly emphasized, given the slow growth rates, low resilience, and limited recovery capacity of deep-sea communities (Tudela & Simard, 2004; Otero & Marín, 2019).

Several RFMOs have established networks of permanent closures to protect VMEs. In the Northwest Atlantic, NAFO has identified and closed numerous areas to bottom fishing to safeguard coral and sponge aggregations, while also delineating bottom-fishing footprints to prevent the expansion of fishing activities into previously unfished and potentially vulnerable habitats (NAFO, 2019). In the Northeast Atlantic, NEAFC has adopted a series of closures covering seamounts, ridges, and other deep-sea habitats in areas along the Mid-Atlantic Ridge and the Hatton–Rockall region (NEAFC, 2014). Comparable spatial management approaches have been adopted by CCAMLR to protect benthic ecosystems in the Southern Ocean, based on encounter data and scientific risk assessments (CCAMLR, 2009).

Permanent area closures provide strong and long-term protection for VMEs by eliminating direct physical disturbance from bottom fishing, and safeguarding ecosystem structure and function (FAO, 2009). However, in data-poor regions, identifying appropriate closure boundaries is often challenging, and precautionary closures may have socio-economic implications for fisheries. To address these challenges, permanent closures are often complemented by adaptive measures such as encounter protocols, move-on rules, and periodic review mechanisms, allowing for the ongoing adjustment of spatial management as new scientific information becomes available (Rogers et al., 2008; Clark et al., 2016).

Fisheries Restricted Areas (FRAs) constitute a set of conservation measures that are specific to the Mediterranean Sea. They represent an additional spatial management tool, under the GFCM, that complements permanent closures by allowing flexible, area-based restrictions tailored to specific conservation and management objectives. Unlike fully closed areas, FRAs may combine spatial and temporal measures, including gear restrictions, effort limitations, or seasonal closures, while still permitting certain fishing activities under defined conditions (FAO, 2016; GFCM, 2018).

FRAs have been increasingly promoted as a key instrument to protect sensitive habitats, reduce fishing pressure on vulnerable species, and support ecosystem-based fisheries management, particularly in data-poor contexts (FAO, 2016; GFCM, 2018; **Figure 5**). By integrating scientific advice, precautionary principles, and adaptive management, FRAs allow management measures to be progressively refined as new ecological and fisheries information becomes available (FAO, 2009; Rogers et al., 2008). In this context, recent discussions within the GFCM have explored the potential extension of the current bottom trawl ban (which is considered a large deep-water FRA) from below 1000 m depth to below 800 m depth, supported by pilot studies indicating limited socio-economic impacts and potential benefits for vulnerable deep-sea ecosystems (Oceana, 2024; FAO, 2025).


**Figure 5.** Map of the Fisheries Restricted Areas (FRA) established in the Mediterranean Sea. The different colours highlight FRAs declared to protect Essential Fish Habitats (in dark blue), Vulnerable Marine Ecosystems (in green), the newest FRA (in dark orange), and the deep-water FRA below 1000m (light blue sea area). (Source: GFCM)

When effectively designed and enforced, FRAs can enhance the protection of VMEs, limit cumulative impacts on benthic habitats, and contribute to the long-term sustainability of fisheries, enhancing the ability of VMEs to cope with climate-driven changes such as warming, deoxygenation, and ocean acidification, and safeguarding carbon stores while mitigating socio-economic impacts through targeted and proportionate restrictions (GFCM, 2018; Clark et al., 2016). It has been demonstrated that VMEs exhibit greater resilience to climate-change stressors when they are not simultaneously exposed to additional human pressures such as bottom trawling and other fishing activities (Morato et al., 2020; Puerta et al., 2020; Buhl-Mortensen et al., 2017; Hennige et al., 2020).

Broad-scale conservation measures are most effective when implemented together. A clear jurisdictional framework that defines permitted depth ranges, restricts the most damaging fishing gear, identifies and introduces reporting protocols, provides multiple, complementary safeguards against habitat degradation. FAO guidance emphasises the importance of adaptive management (i.e. updating measures as habitat mapping and scientific advice improve) as well as transparency, data sharing, and a precautionary approach in deep-sea fisheries management. International and RFMO experience further that enforcement capacity, observer programmes, VMS/AIS data analysis and clear legal instruments are essential to effectively implement and translate regulatory measures into conservation outcomes.

## 4.5 Lessons learned

Experience gained from the implementation of deep-sea conservation measures by various RFMOs highlights several best practices that are particularly relevant for the management of vulnerable marine ecosystems.

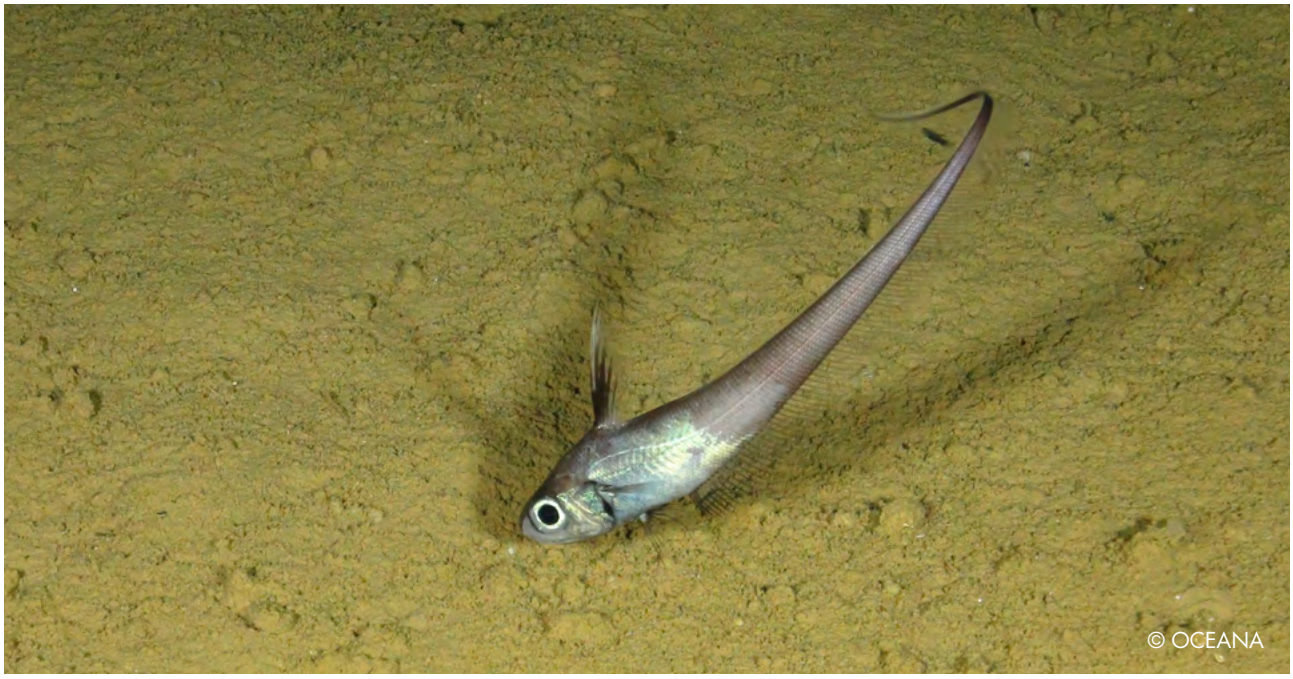
**First**, precautionary approaches have consistently proven to be more effective than reactive management strategies, especially in data-poor deep-sea contexts. Acting before comprehensive habitat mapping or full impact assessments are available reduces the risk of significant adverse impacts on VMEs and helps avoid irreversible ecosystem degradation (UNGA, 2006; FAO, 2009; Clark et al., 2016). This is particularly relevant for the Mediterranean Sea, where deep-sea ecosystems are increasingly exposed to cumulative human pressures and where scientific knowledge remains uneven across regions (Tudela & Simard, 2004; Otero & Marín, 2019).

**Second**, broad-scale measures such as depth-based limits are generally easier to implement, monitor, and enforce than fine-scale, habitat-by-habitat protection schemes. Depth thresholds provide a clear and objective management criterion that can be applied even in the absence of detailed benthic habitat mapping, facilitating compliance and enforcement through vessel monitoring systems and other control tools (FAO, 2009; Rogers et al., 2008). In the Mediterranean, recent assessments have highlighted that extending depth-based restrictions on bottom fishing represents a pragmatic and effective approach to protecting deep-sea habitats and associated ecosystem functions (Oceana, 2024). In this context, FRAs have emerged as a complementary and flexible spatial management tool, allowing targeted and adaptable restrictions on fishing activities while supporting ecosystem-based fisheries management, particularly in data-poor environments (FAO, 2016; GFCM, 2018).

**Finally**, early protection of deep-sea habitats has been shown to prevent permanent ecological damage and to reduce long-term ecological and economic costs. Deep-sea ecosystems play a key role in biogeochemical cycles, including carbon storage and sequestration, and physical disturbance caused by bottom fishing can compromise these

functions for long periods (Borgwardt, 2009; Clark et al., 2016). Recent studies have further shown that fishing activities may conflict with oceanic carbon sequestration processes over significant portions of the ocean, reinforcing the need for precautionary spatial management in deep-sea environments (Sala et al., 2021; Macreadie et al., 2021; Middelburg 2026). Given the extremely slow growth rates and limited recovery potential of many deep-sea species, delayed management action can result in impacts that persist for decades or longer, with limited prospects for recovery (Tudela & Simard, 2004; Otero & Marín, 2019).

Taken together, these lessons learned from RFMO experiences and regional Mediterranean assessments underline the importance of early, precautionary, and enforceable conservation measures — including the use of FRAs — to safeguard deep-sea ecosystems and the services they provide.

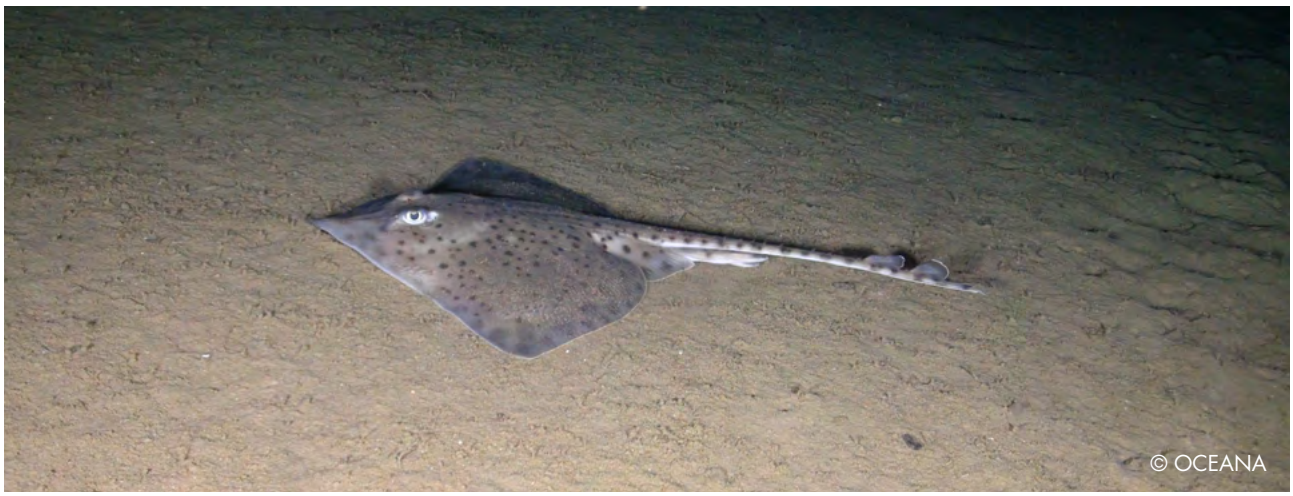
# 5. Five Key Messages for Decision-Makers

## 1. Mediterranean deep-sea ecosystems are globally unique and irreplaceable

Deep Mediterranean waters host a mosaic of vulnerable marine ecosystems (VMEs), (including cold-water corals, sponge grounds, sea pen fields, *Isidella elongata* aggregations, canyons, and seamounts) that support high biodiversity, essential fishery resources, and long-term carbon sequestration. Despite their low apparent productivity, these ecosystems have a disproportionately high ecological value.

## 2. These ecosystems are extremely vulnerable and recover over century-long timescales

Deep-sea species are slow-growing, long-lived, and exhibit very limited resilience. The ecosystems they form are highly vulnerable to impacts and slow to recover, meaning that physical disturbance from fishing can lead to irreversible habitat loss and long-term declines in associated fauna.




## 3. Bottom-contact fishing is the main driver of degradation and threatens fisheries sustainability

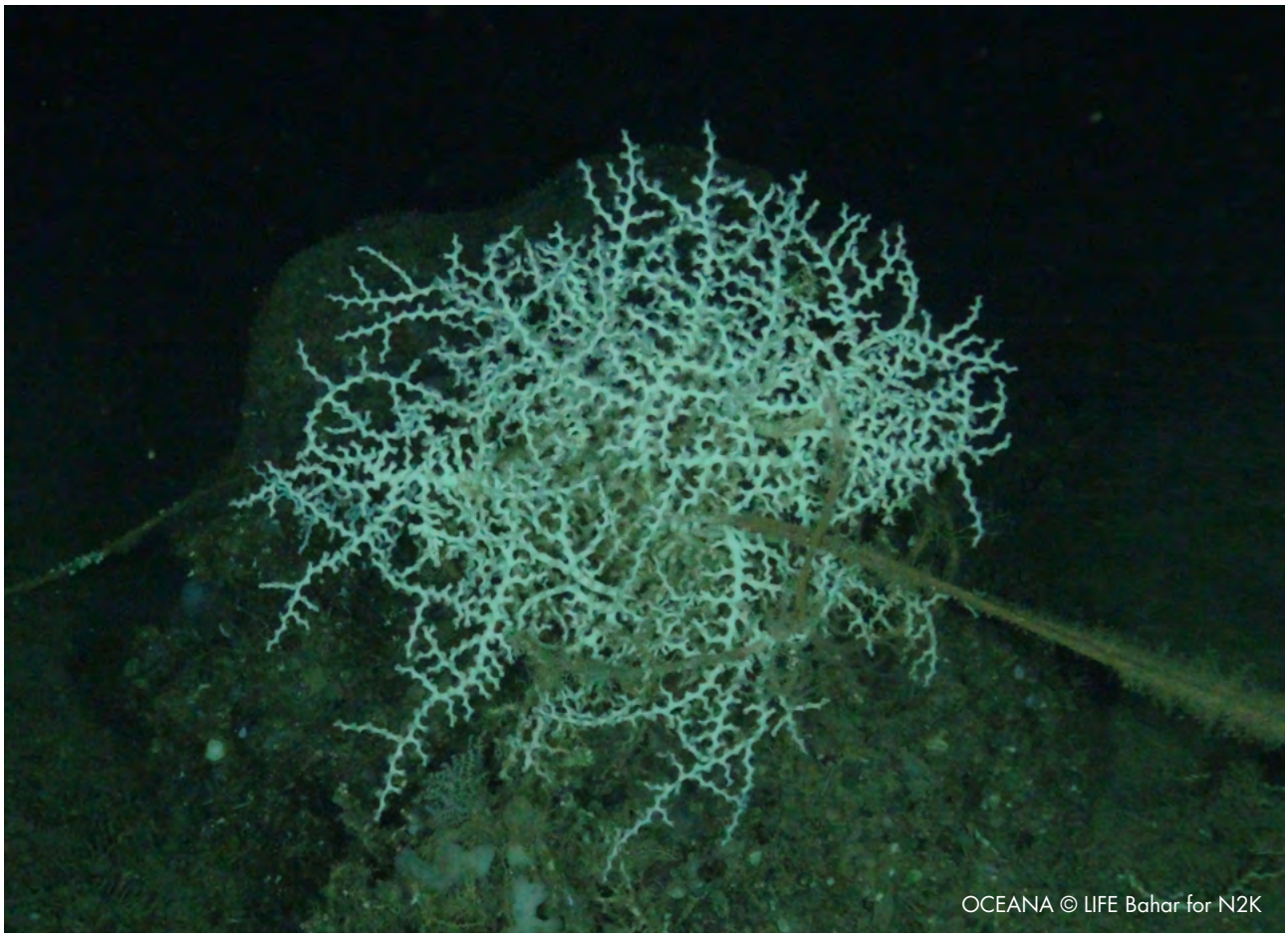
Bottom-contact fishing, such as bottom trawling, removes habitat-forming species, homogenizes sediments, disrupts key linkages between the seafloor and the water column, and reduces the efficiency of carbon burial. Documented impacts across the Mediterranean include the near-collapse of *Isidella elongata* colonies, persistent damage to coral and sponge communities, sediment resuspension, and organic carbon loss, as well as reduced habitat complexity and slow recovery rates, ultimately undermining the productivity of demersal stocks.

# 4. Climate change is accelerating vulnerability and shrinking suitable habitats

Rapid warming, deoxygenation, and declining food supply are already affecting deep-sea species. Habitat suitability models project significant losses for key VME taxa under high-emission scenarios, with suitable habitats shifting deeper. Without protective precautionary measures, climate and fishing pressures will interact, reducing resilience and accelerating ecosystem decline.

# 5. Extending the 1000 m FRA to waters below 600-800 m depth is scientifically justified, precautionary, and aligned with global RFMOs practice

International RFMOs (NAFO, NEAFC, CCAMLR, SPRFMO) have adopted broad-scale depth-based closures, typically below 600–800 m depth, to protect VMEs in data-poor contexts. Extending the current Mediterranean trawl closure from below 1000 m to below 600-800 m would safeguard the depth range where VMEs are most concentrated, reduce cumulative impacts, enhance climate-refugia and seabed carbon storage potential, and support the GFCM 2030 Strategy and CBD targets. It is a feasible, enforceable, and urgently needed measure.



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