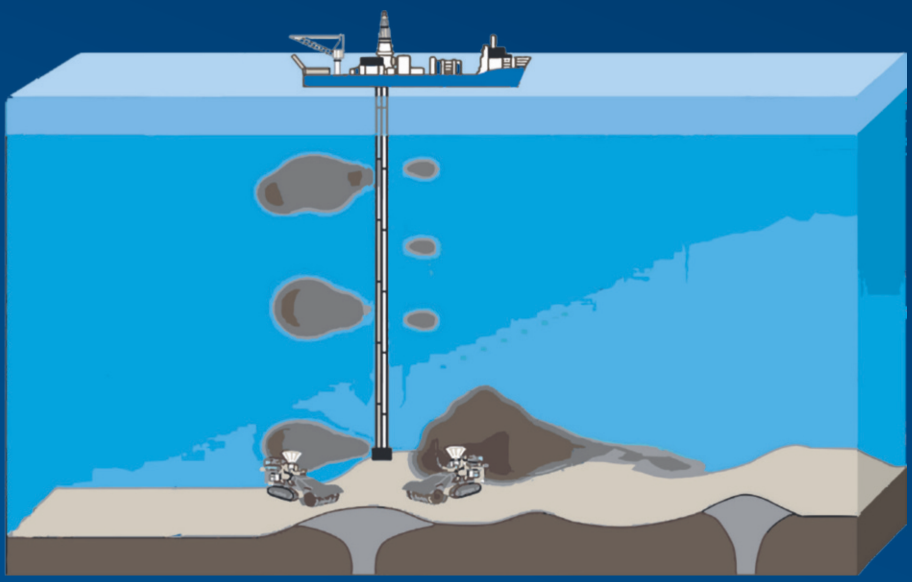
Rahul Sharma *Editor*

Deep-Sea Mining and the Water Column

Advances, Monitoring and Related Issues



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Cover image: Schematic of Deep-sea mining system and associated impacts on the pelagic and benthic ecosystems (Modified from original diagram from NIWA-IUCN, figure provided by Malcolm Clark).

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Foreword

I am delighted at receiving the invitation to contribute a foreword for the fourth book by Dr. Rahul Sharma on the topic of deep-sea mining. As with previous volumes, it is a great honour for me to accede to his request.

As the International Seabed Authority progresses its work on the regulatory framework for the inevitable transition from deep-sea mineral exploration to exploitation, the public debate on the topic has become increasingly polarized and frequently misinformed. A few sectors of society have even been calling for a moratorium on all deep-sea mineral activities, notwithstanding that these activities are fully regulated by international law and that deep-sea exploration has in fact provided considerable benefit to humankind through increased scientific knowledge and technological development.

Dr. Sharma's earlier volumes, on the resource potential and technical considerations for deep sea mining (2017), on environmental issues of deep-sea mining (2019), and on sustainability, technology, environmental policy and management (2022), contributed greatly to the scholarly literature on deep-sea mining and brought together the perspectives of experts in the field, including many of the world's leading experts in their subjects.

The present volume addresses the topic from the perspective of the water column, which has a unique significance being the large volume of water mass that will likely be impacted upon and in turn influence decisions related to offshore mining in future. Of particular importance is the fact that, rather than advancing political positions, most of the contributions to the book critically address the way in which the main expected impacts of deep-sea mining can be predicted, measured and mitigated, not least through the rapid maturation of technology that, for the most part, remains under development.

There is no doubt that, as with every other human endeavour, there are pros and cons to deep-sea mining. However, in the short to medium term, it seems likely that a mix of critical minerals from land and sea can more sustainably support the energy transition than relying on terrestrial sources alone. Deep-sea mining thus presents an important opportunity for development. But more technical, impartial and informed discussion is needed, especially on economic, geological and technological aspects, and Dr. Sharma's book makes an important contribution in this respect.

I congratulate Dr. Sharma and all the experts who have contributed to this volume.

Secretary-General
International Seabed Authority,
Kingston, Jamaica
September 2023

Michael W. Lodge

Preface

Deep-sea mining has been a topic of interest in recent years, as after the signing of exploration contracts between the International Seabed Authority (ISA) and several entities for different types of mineral deposits from the deep-sea regions in international areas, the focus is shifting to development and testing of various subsystems for mining and processing of these deep-sea minerals, as well as on the deliberations that are underway at ISA for developing a mining code. Similar efforts are underway for exploration and exploitation of deep-sea minerals within the Exclusive Economic Zones of several countries.

In this series on deep-sea mining, while the earlier three editions have focused on *Deep-sea mining: Resource Potential, Technical and Environmental Considerations*, *Environmental Issues of Deep-Sea Mining: Impacts, Consequences and Policy Perspectives* and *Perspectives on Deep-Sea Mining: Sustainability, Technology, Environmental Policy and Management*, this book deals with *Deep-Sea Mining and the Water Column: Advances, Monitoring and Related Issues*.

It is anticipated that the water column could be the largest volume of water mass that would come in contact with various subsystems as well as the effluents that may be discharged during deep-sea mining operations, leading to impacts on the marine ecosystem. This could lead to various environmental as well as legal issues, since the area impacted in the water column could be larger than the one impacted on the seafloor where mining would take place.

Hence, this book contains sections dealing with general issues of deep-sea mining; engineering concepts; approaches to sea surface and water column monitoring; regional assessment of chemical, physical and biological characteristics of water column; and the legal, policy and economic issues. This book has been possible due to the excellent contributions by researchers from around the world, who have shared their expertise for the benefit of deep-sea community in particular and the humankind in general.

As this book contains articles from authors from diverse backgrounds, readers are requested to note that the views expressed are those of individual authors and do not reflect the view of either the editor or that of the publisher.

The editor is extremely grateful to all the authors for sparing their time and contributing to this book. Mr. Michael Lodge, His Excellency, the Secretary General of ISA, deserves a special mention for his Foreword that sets the tone of the book. A special thanks goes to Dr. Virginie Tilot, Attaché honoraire, Museum National D'Histoire Naturelle, Paris, France, not only for suggesting the theme 'Deep-sea mining and the water column' but also for her constant support during the compilation of the book.

It is expected that this book will serve as an important source of information on different aspects of deep-sea mining with a special focus on the water column, for all stakeholders including the researchers, technologists, contractors, mining companies, regulators and the NGOs involved in deep-sea mining and marine environmental conservation.

Dona Paula, Goa, India Rahul Sharma

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Chapter 13
Multilevel Assessment and Options for the Management of Cumulative Impacts on Pelagic Ecosystems in the North-Eastern Tropical Pacific Ocean

Virginie Tilot, Léa Fourchault, Alain Jeudy de Grissac, Jérôme Mallefet, and Juan Moreno Navas

Abstract The multilevel assessment of the water column located above the seabed of the Clarion-Clipperton Zone, an area rich in mineral resources targeted for the mining industry, first reveals that interconnected ecological and oceanographic processes support numerous ecosystem services. As a result, the cumulative impacts of fishing, deep-sea mining, shipping, and climate change on organisms across the epi-, meso-, and bathy-pelagic layers of this region are highlighted, as well as their impact on ecosystem services. Finally, management measures and conservation strategies are proposed, highlighting the socio-ecological interconnectivity between marine life and humans, to foster sustainable ecosystem services for global human well-being and to ensure sustainable livelihoods for the Pacific communities.

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Keywords Deep-sea mining · Water column · Pelagic · Ecosystem services · Fisheries · Anthropogenic and natural impacts · Sediment plumes · Conservation strategies · Socio-ecological interconnectivity · Management measures

1 Introduction

The Clarion-Clipperton Zone (CCZ), located in the north-eastern tropical Pacific (118°–157° W/9°–16° N), holds the most commercially interesting marine polymetallic nodule deposits globally (Morgan, 2000; Petersen et al., 2016). Following prospects of deep-sea mining (DSM) activities, a comprehensive study of the biodiversity and distribution of epibenthic megafauna of the CCZ, serving as a baseline study (Tilot, 2006a, b), led to the development of several propositions of conservation strategy and management tools in view of the assessed impacts (ESCO CNRS IFREMER, 2014; Tilot, 2010, 2013, 2014, 2019; Tilot et al., 2018).

This chapter furthers this approach to highlight potential cumulative impacts resulting from DSM and other anthropogenic activities as well as global change on ecosystems found throughout the eastern Pacific's water column (Willett et al., 2006; Tilot, 2010, 2019; Jones et al., 2017; Levin et al., 2018; Tilot et al., 2018; Sharma, 2019; Christiansen et al., 2020; Blanluet et al., 2023). Strategies for the conservation of pelagic ecosystems in this area are suggested, highlighting the socio-ecological interconnectivity between marine life and humans to ensure sustained ecosystems services for human well-being and sustainable livelihoods for Pacific communities (Tilot et al., 2021a, b, c).

2 Physical and Chemical Properties of the Water Column in the CCZ

Marine ecosystems in open systems are in constant flux and can be affected by marine and climatic parameters generated locally and elsewhere. Such ecosystems are characterized by short-term perturbations and disruptions as well as by more regular, seasonal patterns according to which marine species adapt their life cycle patterns. The physical and chemical characteristics shaping pelagic ecosystems in the tropical north-eastern Pacific display a considerable regional-scale variation, as outlined in the following paragraphs.

2.1 Surface Currents and Eddies

Surface currents influence many of the ocean patterns, dynamics, and processes observed in the CCZ. The eastern Pacific is characterized by two cold-water boundary currents: the southward flowing California Current in the north and the northward flowing Peru Current in the south (Fiedler & Talley, 2006).

The CCZ itself is dominated by the North Equatorial Current (NEC, 8 °N – 20°N). This broad westward flow of the subtropical gyre brings comparatively richer waters from the easternmost Pacific Ocean to the CCZ (Fiedler & Talley, 2006; Kessler, 2006). Another important current in the southern CCZ is the strong eastward flowing North Equatorial Counter-current (NECC, 5°N and 10°N). Both the NEC and NECC have mean speeds of 0.4 knots at a depth of 20 m, decreasing to 0.2 knots at 300 m to become relatively weak (0.08–0.15 knots) at 300–4800 m depths (Worthington, 1981).

These equatorial currents are complemented by eddies, i.e., circulations of about 50–200 km diameter in surface, often variable over a period of weeks to months (Talley et al., 1998). Their presence results in sea-surface elevation variability of 4 cm or more over the CCZ, caused by excess kinetic energy (Hollister & Nowell, 1991; Kontar & Sokov, 1994). The occurrence of eddies is higher over the eastern part of the CCZ, where it produces greater mixing (Chang et al., 2012; Purkiani et al., 2020).

2.2 Midwater Circulation

Maps of net transport and circulation from 500 to 1500 m in the equatorial Pacific exhibit two almost symmetrical cyclonic gyres between 15°S and 15°N for the Equatorial Pacific Intermediate Water (EqIW) (Bostock et al., 2010; Reid, 1997). Intermediate waters in the CCZ are formed through influx of North Pacific Intermediate Waters into the North EqIW, and circulation patterns broadly mirror surface circulation (Fig. 13.1, Bostock et al., 2010).

2.3 Deep Circulation

Bottom currents in the north-eastern tropical Pacific also broadly mirror surface currents, and are predominantly weak (Shor, 1959), between 2 and 25 cm/s (Amos et al., 1977). The flow is characterized by alternating periods of stronger, quasi-unidirectional currents and periods of sluggish water movement (McCartney, 1982; Kontar & Sokov, 1994, 1997). Specifically, sediment distribution in the deep Pacific basin is controlled by the western, northward flowing Lower Circum Polar Water (LCPW), which is characterized by low bottom current velocities and high oxygen concentrations. The LCPW becomes the North Pacific Deep Water (NPDW) in the central-north Pacific, as the LCPW warms and gains silica. The southward flow of NPDW bounds the CCZ in the east, bringing these deep polar waters (Hayes, 1979; Mewes et al., 2014).

The surface and deeper currents are strongly coupled to each other, as evidenced in ocean modeling, where subsurface flows dive down the water column to merge into the deep circulation. There are local accelerations of flow caused by the morphology of the seabed, where rises and seamounts strongly steer bottom flows. Several hydrographic disturbances, such as periodic benthic storms, have been recorded during long-term in situ monitoring (Gardner et al., 1984; Richardson

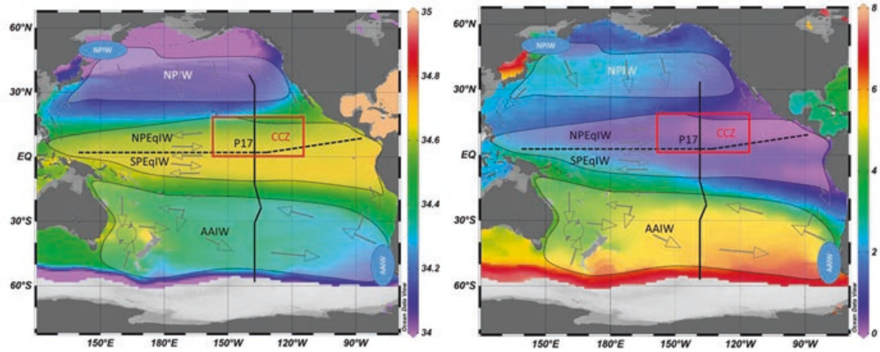

Fig. 13.1 Map view of the (**a**) salinity and (**b**) oxygen concentration (mmol l^{-1}) at the Pacific basin scale (along the potential density (sigma theta) of 27.1 kg m^{-3}), highlighting currents and water masses. The possible midwater circulation is depicted by the gray arrows. Formation regions of North Pacific Intermediate Water (NPIW) and Antarctic Intermediate Water (AAIW) are represented in blue circles. Intermediate waters are shaded in light gray (NEqPIW—North Equatorial Pacific Intermediate Water; SEqPIW—South Equatorial Pacific Intermediate Water), separated by regions of mixing. The CCZ is framed by the red box. (Adapted from Bostock et al. 2010)

et al., 1993; Kontar & Sokov, 1994; Aller, 1997). During benthic storms, cold currents flowing toward the equator in the deep ocean are accelerated into powerful sediment-transporting events, associated with a deep-reaching anticyclonic eddy (Hollister & Nowell 1991).

2.4 Water Masses

The water body in the CCZ is divided into three layers: an upper mixed layer that overlies a strong permanent thermocline and a deep layer.

First, the *upper* 500 m of the north-eastern tropical Pacific can be divided into three layers: (1) a top layer of weak temperature and salinity gradients extending from the surface up to 100 m depth, (2) a sharp thermocline with temperature gradients from 28 to 12 °C, over a water depth of approximately 100 m, and (3) a region of lower stratification below the thermocline, with a salinity maximum (Wijffels et al., 1996). These upper layers include the Pacific Equatorial Water, strongly linked to the El-Nino cycle, and the Eastern North Pacific Central Water (Emery, 2003).

The upper layer varies in thickness as it is related to seasonal variations in wind and wave conditions. Overall, temperatures are several degrees cooler in the north-eastern tropical Pacific due to the thermal structure of the upper ocean where the surface water mass layer is shallower (<100 m thick) and the thermocline closer to the surface caused by the upwelling along the coasts of the Americas and the eastern boundary currents which flow toward the equator (Wyrtki & Kilonsky, 1984).

Second, *intermediate waters* in oceanic basins comprise a range of depths between 550 and 1500 m, as the strong permanent thermocline separating the surface and intermediate waters exhibits seasonal variability (Emery, 2003). Despite this variability, three major intermediate water masses have been identified in the Pacific Ocean, based on temperature and salinity diagrams: North Pacific Intermediate Waters, Antarctic Intermediate Waters (Bostock et al., 2010; Dickson et al., 2001; Talley, 1993), and an Equatorial Pacific Intermediate Water, which dominates the CCZ (Figs. 13.1 and 13.2, Bingham & Lukas, 1995; Bostock et al., 2010; Wijffels, 1996*;* Bostock et al., 2010).

The North Pacific Intermediate Water appears from 400 to 800 m and is characterized by a salinity minimum (reaching 33.8 ppm/ppt), low oxygen concentrations (50–150 mmol kg-1), and low density (26.4–27.2 g/cm^3) (Dickson et al., 2001, Talley et al., 2011). Antarctic Intermediate Waters presents a high oxygen content (200–250 mmol kg^{-1}), a minimum salinity (34.3–34.533.8 ppm/ppt), and a temperature range from 3.5 to 10 °C, resulting in an average density of 27.1 g/cm^3 (Bostock et al., 2010; Tsuchiya & Talley, 1996). The coldest branch of the Antarctic Intermediate Water at 3.1 °C (McCartney, 1982; Talley, 1993) is slightly present in the CCZ (0.9%) (Catala et al., 2015a, b; Tilot et al., 2018).

From the analysis of water samples collected between 7 °N – 20 °N and 99 °W – 167 °W during the Malaspina 2010 circumnavigation, the thermohaline and intermediate waters in the CCZ present unique features. The water masses associated to this region undergo excessive aging, i.e., the oxygen consumption is higher than expected (Catalá et al., 2015a, b; Feely et al., 2004). This anomaly is associated with (1) the comparatively high biological productivity of the south-eastern part of the area, which exports organic material from the surface to the deep ocean (Feely et al., 2004) and (2) the sluggish deep circulation of the North Pacific, which facilitates organic matter sinking.

Last, the *deep-water* stratification near the seabed is weak in the CCZ (Hayes, 1979), in a very narrow range of temperature and salinity (1.2 °C and 34.70 PSU). These oldest water masses, located in the north-eastern Pacific between 1800 and 3500 m (Talley et al., 2011), are characterized by a distinct biogeochemistry, and greater molecular diversity, heterogeneity, and complexity of dissolved organic matter (Dittmar, 2015). Local microbial communities are expected to be adapted to hypoxic conditions, resulting in a different deep-sea microbial biodiversity. Both biochemistry and microbial communities are likely to influence the nodule ecosystem via pelagic-benthic transfers to the sediments.

2.5 Topography, Habitats, and Eco-hydrodynamics

The bottom depth in CCZ varies between 3800 and 4000 m in the eastern region and between 5400 and 5600 m in the western region. The seabed topography is mainly composed of abyssal hills, elongated in a north to south direction and running parallel to each other (Fig. 13.3). These hills have irregular, elliptically domed summits,

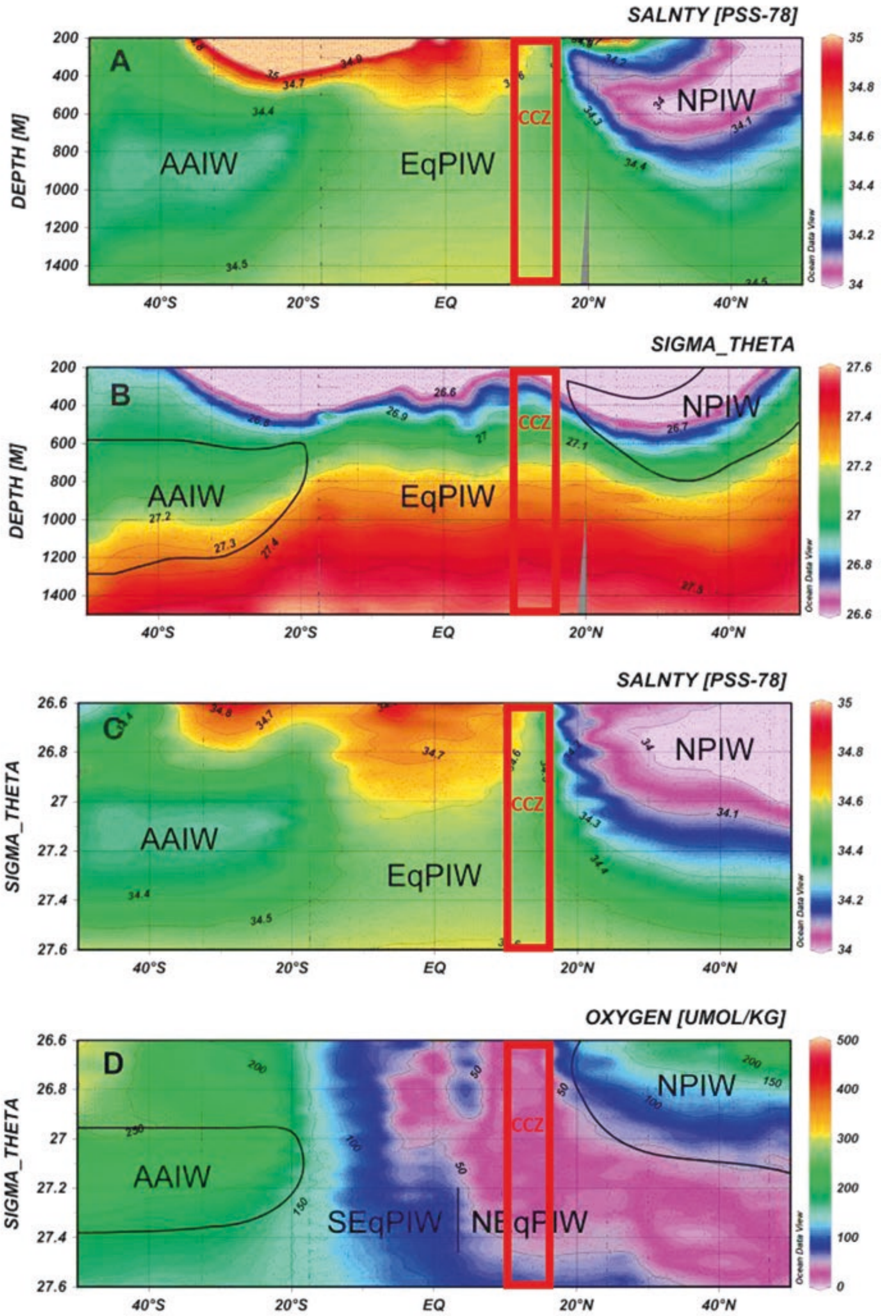

Fig. 13.2 North to south transect along the 140°W Meridian showing the intermediate waters characterizing the Pacific. The CCZ is located between 9 and 16°N (red box). Distribution of different parameters and derived variables with depth (200–1500 m): (**a**) Salinity and (**b**) potential density (sigma theta), with the salinity contour overlaid from A. Distribution of different parameters with potential density: (**c**) Salinity and (**d**) oxygen, with the contour overlaid from **c**. (Adapted from Bostock et al. 2010)

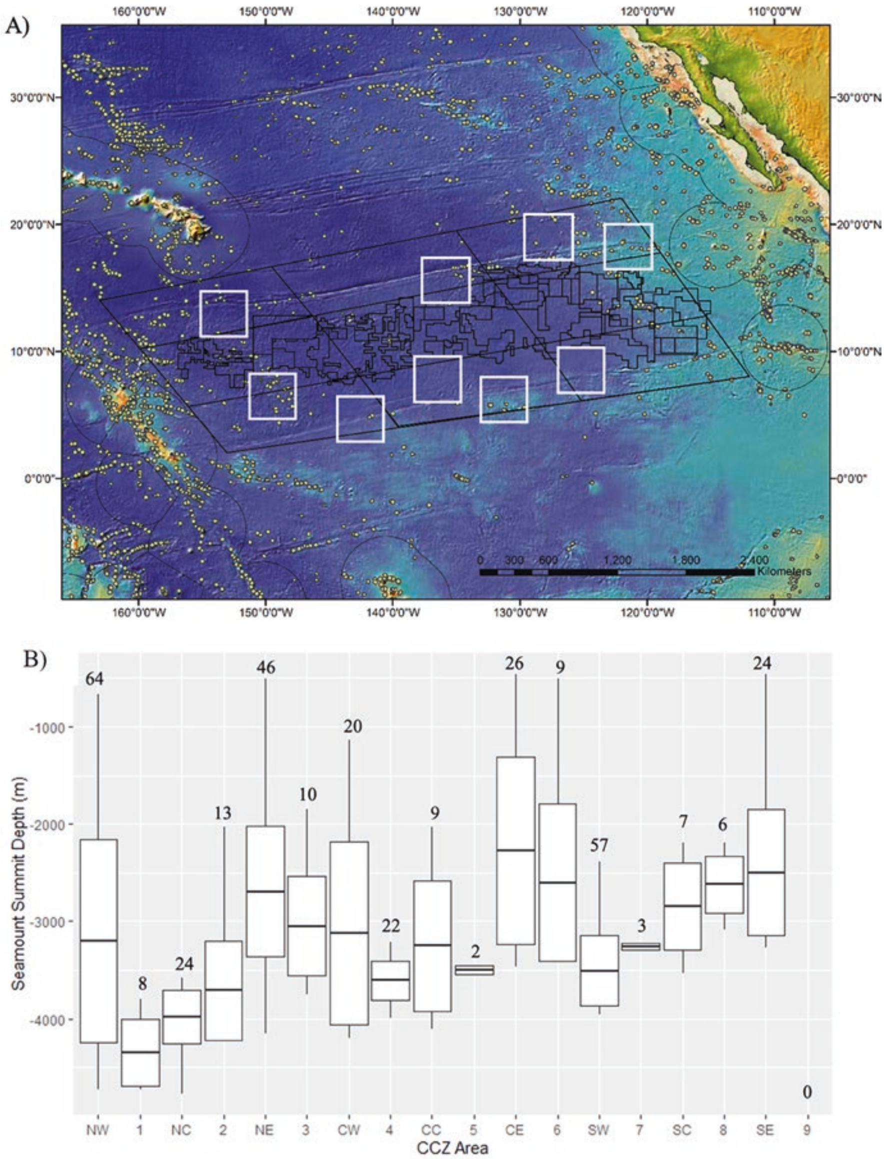

Fig. 13.3 Topographic characteristics of the CCZ: knolls, seamounts, and depth (Washburn et al., 2021). Depth (in meters) at a 1-minute resolution downloaded from ETOPO1. There is a bar for each CCZ subregion (NW northwest, NC northcentral, NE northeast, CW central west, CC central central, CE central east, SW southwest, SC southcentral, SE southeast) and Areas of Particular Environmental Interest (APEI) designated by ISA (APEIs 1–9). Each APEI follows the subregion it is meant to represent. Seamounts (**a**) and knolls (**c**) (in yellow) were identified using global bathymetric data at a 30 arc second resolution. Bar graphs for depth at a 0.5-degree resolution (in meters). Thick, black bars represent means, the lower and upper edges of the boxes represent 1 standard deviation, and the lower and upper edges of the lines represent minimums and maximums

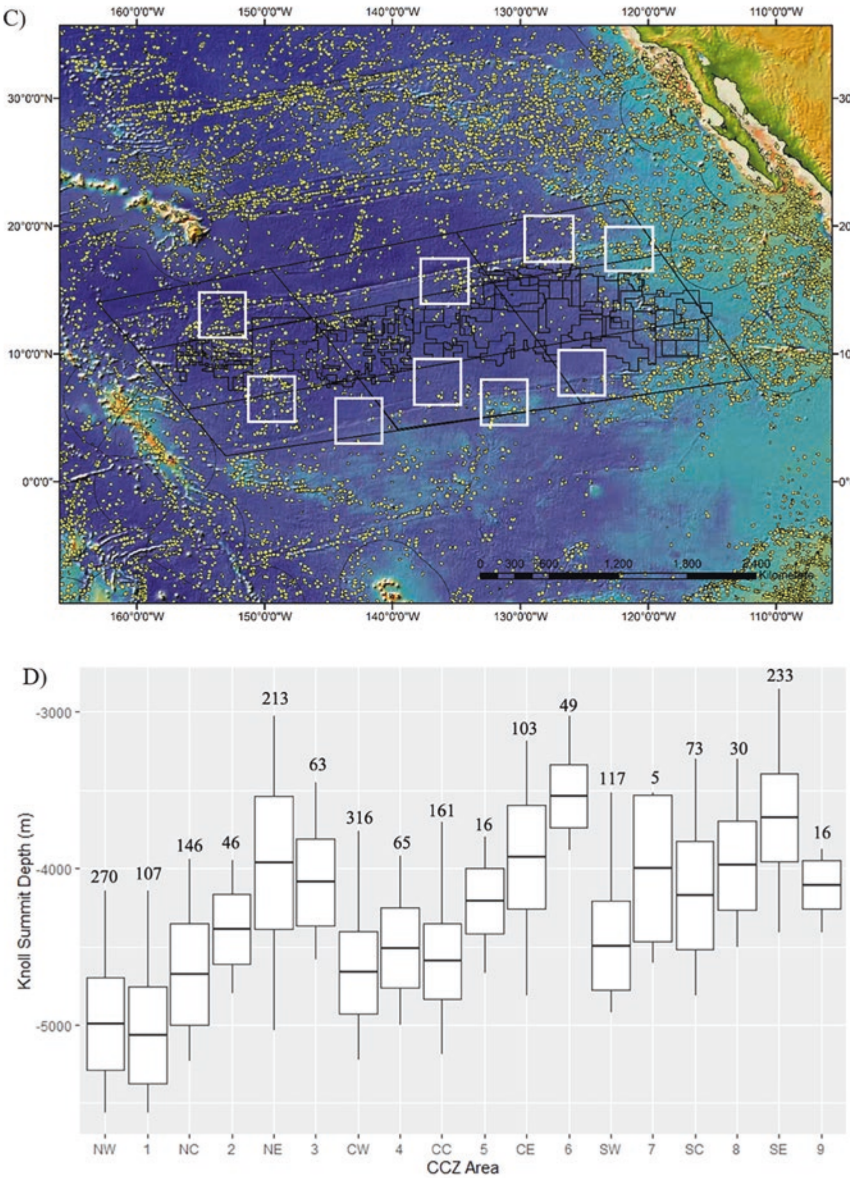

Fig. 13.3 (continued)

and steep, sometimes escarpment-like sides. Vertical cliffs of calcareous clay up to 40 m high occur on the flanks of the hills, and large potholes have been found on the crests that rise 100–300 m above the lowest areas (Menard, 1964; Halbach et al., 1988; Juan et al., 2018; Kotlinski, 1998; Washburn et al., 2021). Sediments are covered by nodule fields interspersed with some nodule-free sediment areas (Hoffert,

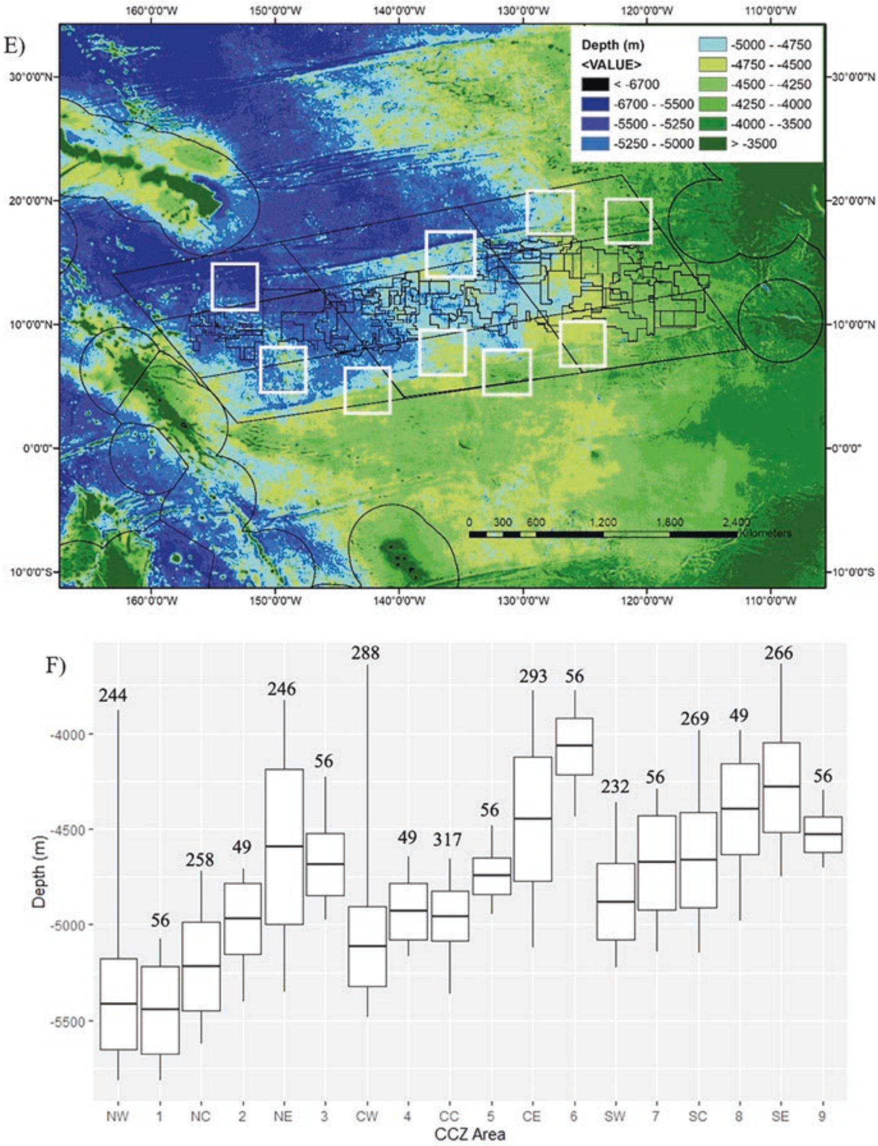

Fig. 13.3 (continued)

2008). In the eastern tropical Pacific, sediment coverage is about 20% thicker within morphological depressions than on the ridges. Sediment thickness increases westward from 50 to 150 m between 120° and 155°W longitude. Locally at some sites, seabed morphology comprises horsts and grabens that tend to generate stronger currents on slopes. Under the influence of sedimentary processes, the contours tend to soften (Shor, 1959).

The CCZ hosts 387 seamounts (>1000 m from the sea floor) and numerous knolls (200–1000 m) and highs (<200 m), especially in its eastern and western peripheries (Macdonald et al., 1996; Washburn et al., 2021) (Fig. 13.3a–f). Cobaltiferous crusts have been found on certain escarpments, rocky plateaus, ridges, and seamounts in the CCZ. Their thickness ranges from a few decimeters to a few meters, depending on the age of the seamounts (Macdonald et al., 1996; Washburn et al., 2021). This habitat heterogeneity locally increases the strength of currents, which influences biodiversity, especially with regard to suspension feeders (Tilot, 2006a, b, Tilot et al., 2018).

Larger seamounts, particularly when closer to the surface, can create local upwellings, eddies, and Taylor columns—a fluid dynamics phenomenon enhanced by the Coriolis effect. This results in higher surface productivity and supports a wide range of pelagic species, including sharks, tunas, and billfish (Morato et al., 2010; Watling & Auster, 2017).

2.6 Geophysical Parameters and Primary Productivity

The CCZ is in the pelagic bioregion of the Eastern Tropical Pacific (ETP) (UNESCO, 2009). The entire ETP is defined by a strong, shallow thermocline, a pronounced oxygen minimum zone, ranging from 250 to 2250 m with the lowest values at 500–750 m, and decadal El Niño Southern Oscillation (ENSO) variability (Willett et al., 2006; Longhurst, 2007).

In the eastern tropical Pacific, nitrate and phosphate concentrations are low in the upper layer due to uptake by photosynthesizing organisms. A nutrient maximum appears in the intermediate layer—centered at 1000 m depth, where rates of decomposition are high and rates of photosynthesis are low—followed by a decrease in nitrate concentration with increasing depth. Dissolved silica concentrations are low in the upper mixed layer due to uptake by phytoplankton, with dissolved silica concentrations increasing with increasing water column depth (Pennington et al., 2006; Vasiliu et al., 2022).

The overall primary productivity, particulate organic carbon fluxes, and trophic input primary productivity in the CCZ are comparatively low (Smith & Demopoulos, 2003; Pennington et al., 2006). For instance, particulate organic carbon fluxes range from 0.5 to 1.6 g C $m^{-2}year^{-1}$, placing the CCZ within the broadly defined mesotrophic abyss, as defined by Hannides and Smith (2003). However, considerable variation in the vertical flow of particles has been described (Karl et al., 1996; Baldwin et al., 1998; Karl, 2002; Smith & Rabouille, 2002), in line with seasonal patterns, upwelling, and El Niño events (Dymond & Collier, 1988; Ruhl & Smith, 2004). The openness of the ocean system leads to a dynamic and highly variable benthic-pelagic coupling (Rowe, 1971; Pfannkuche & Lochte, 1993) which results in variable sinking patterns of marine snow and consequently patches of deposition of phytodetritus on the seafloor (Smith et al., 1997, 2008a; Beaulieu & Smith, 1998). This causes significant changes in the structure of both benthic and pelagic faunal

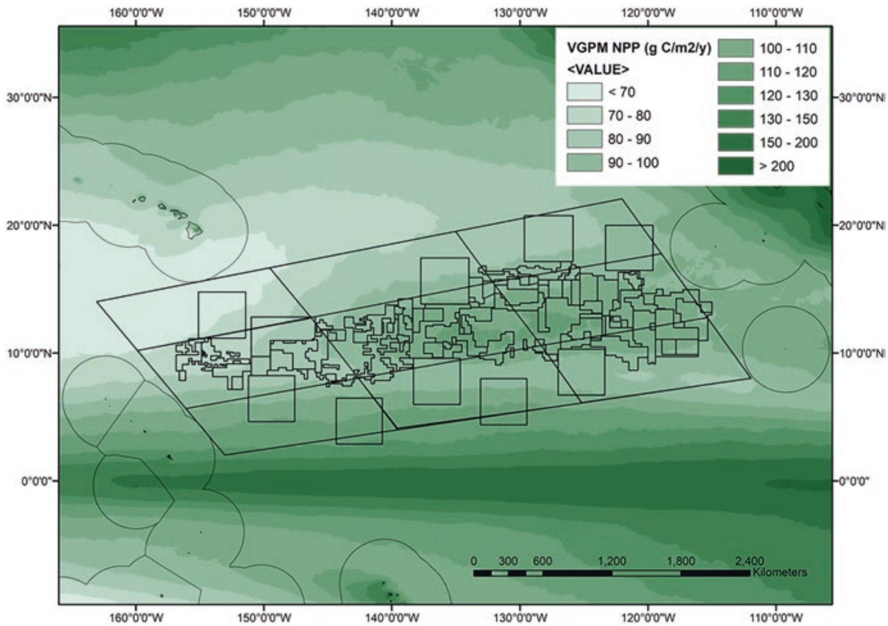

Fig. 13.4 Net primary productivity over the CCZ (Washburn et al., 2021). VGPM: vertically generalized production model. NPP: net primary productivity. Dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) display spatial variability in the upper ocean, with higher nutrient concentrations at low latitudes and a marked nutricline in the eastern region at ~150 m (DIN, ~32.0 μmol/L; DIP, ~2.4 μmol/L). Conversely, they are lower (DIN, ~1.2 μmol/L; DIP, ~0.1 μmol/L; at ~150 m) at high latitudes and in the western region, where there is no nutricline. Nutrient concentrations are more homogeneous spatially at greater depths. (Han et al., 2022)

assemblages and measurable effects on ecosystem functions (Smith et al., 1993; Lauerman et al., 1997; Drazen et al., 1998; Thurston et al., 1998; Danovaro, 2008; Loreau, 2008).

Overall, a marked spatial variation in net primary productivity can be observed in the water column above the CCZ, with east-west and north-south gradients in nutrient concentrations for upper layers (Fig. 13.4, Washburn et al., 2021). In the eastern CCZ, a moderate temporal variation has recently been observed, with higher temperatures, chlorophyll a, and particulate organic carbon concentrations from June to November (Gillard et al., 2022). This seasonality is likely caused by the meridional migration of the intertropical convergence zone (Amador et al., 2006). Nonetheless, productivity levels remain comparatively stable throughout the year (Fiedler & Talley, 2006).

Other than the varying vertical deposition of phyto-detritus, three major factors contribute to trophic input and distribution, hence influencing the structure of faunal assemblages. First, currents originating in zones of higher primary production can horizontally contribute suspended nutritive sediment particles. Second, certain edaphic and hydrological conditions above the bottom layer, likely related to the topography of the ocean floor, can favor the collection of nutritive sediment particles. Last, the sinking carcasses of pelagic organisms provide a significant input of carbon to benthic food webs (Dayton & Hessler, 1972; Haedrich & Rowe, 1977; Smith & Baco, 2003; Tyler, 2003).

3 Pelagic Life Forms: Diversity, Distribution, Connectivity, and Ecosystem Services

Despite their importance as the greatest source of biomass in the world, deep pelagic communities have long been the most understudied organisms (Webb et al., 2010). In the mesopelagic (200–1000 m depth), bathypelagic (1000–4000 m), and abyssopelagic realms (4000–6000 m), taxonomy, biodiversity, and functional relationships within ecosystems are still poorly described (Robison, 1992; Christiansen et al., 2020). However, deep pelagics are likely to play a significant role in the provision of ecosystem services on a global scale, nutrient cycling supporting fisheries, and carbon sequestration regulating the global climate (Jones et al., 1994; O'Leary & Roberts, 2017). Well-known examples of ecosystem engineers in the open ocean include phytoplankton and zooplankton (Jones et al., 1994; Breitburg et al., 2010), and baleen and sperm whales (Roman et al., 2014).

Numerous pelagic species use the CCZ for feeding, migration, and reproduction near the surface and extend their range to greater depths into the meso- and even bathypelagic (1000–4000 m) layers (Thorold et al., 2014; Abascal et al., 2010; Fuller et al., 2015; Howey et al., 2016).

3.1 Phytoplankton

Primary production of phytoplankton is dominant in the open ocean and comprises nearly half of the annual global net primary production (Field et al., 1998; Falkowski, 2012; Siegel et al., 2013). Through photosynthesis, organic matter fuels the metabolic demands of marine ecosystems and has an important regulatory function in the global carbon cycle, acting as biological pump sending carbon dioxide to the deep ocean (Siegel et al., 2013; Falkowski, 2012). Evidence has shown that changes in temperature, irradiance, nutrient, and physical circulation of the atmosphere and ocean affect phytoplankton production, as seen with algal blooms associated with El Niño (Falkowski, 2012; Not et al., 2012; Siegel et al., 2013; Chen et al., 2017). Notably, long-term data from the north-eastern Pacific show that variations in climate and surface primary productivity, as indicated for instance by the Bakun Upwelling Index, were significantly correlated with the flux of particulate organic carbon at 3500 m depth when lagged by 2–3 months (Smith et al., 2009).

Primary productivity in the CCZ is spatially patchy with significant temporal variability preventing homogenous mixing of deeper nutrient-rich waters with the surface waters (Peña et al., 1990; Pennington et al., 2006). The vertical distribution of phytoplankton is characterized by a peak in abundance within the mixed layer (first 50 m) of the water column, where the flux of organic matter is maximal (Kirchman, 2008). Because of the elevated primary productivity in the south-eastern part of the epipelagic layer of the CCZ, the water column below this layer is considered a hotspot for abyssal biodiversity in the region (Smith et al., 2008, Hernández-León et al., 2020).

3.2 Zooplankton

The large deep-sea zooplankton biomass mirrors primary production in the global ocean (Hernández-León et al., 2020). Zooplankton also participate in the fixation of carbon from the surface to the seabed. Through their vertical migrations (up to 500 m), zooplanktonic organisms ingest food near the surface, which becomes available to deep-sea organisms through excretion, respiration, or predation in deeper layers (Jónasdóttir et al., 2015; Sutton et al., 2017; Turner, 2015). This active flux likely represents 10–50% of the total vertical flux of carbon downward from surface waters (Turner, 2015). Global annual respiration of meso-zooplankton (e.g., copepods) across all depth zones of the ocean has been estimated between 8.8 and 17.2 billion tonnes of carbon, representing 17–32% of global open ocean primary productivity (Hernández-León & Ikeda, 2005).

Zooplankton in the CCZ includes both primary and secondary consumers of a broad taxonomic composition, such as fish larvae (ichthyoplankton), coelenterates (e.g., jellyfish), copepods, and chaetognaths (arrow worms). Within the eastern tropical Pacific, copepods and krill (euphausiid crustaceans) are the most important zooplankton groups in terms of biomass (Brinton, 1979). The vertical distribution of zooplankton is forced by the strong thermocline and the oxygen minimum zone, which occurs below the thermocline and extends down to 600–800 m beneath the surface. The abundance of zooplankton in the CCZ fluctuates relatively little throughout the year, as it is the case for most of the open ocean in the ETP area (Fernández Álamo & Färber Lorda, 2006).

3.3 Invertebrate Nekton

Invertebrate nekton in the CCZ, though poorly known, predominantly belongs to the cephalopods (e.g., phylum Mollusca) or crustaceans (e.g., phylum Arthropoda). Pelagic cephalopods, including squids, form the intermediate step between the micronekton and top pelagic predators such as commercially important tuna and swordfish, mammals, seabirds, and sharks (Young et al., 2013). In line with its dependence on nutrients from epipelagic layers, deep-sea nekton is likely more abundant in the eastern part of the CCZ.

3.4 Mesopelagic Fishes

Mesopelagic fishes are likely the most abundant vertebrates on Earth, with an estimated global biomass of 10 billion tons, representing the largest structuring biomass in the open sea (Irigoien et al., 2014). Due to limited food availability, fishes in the deeper parts of the midwater environment typically have lower metabolic rates, softer skeletons, and reduced protein levels, and they respond to cyclic hydrodynamic patterns and periodic fluctuations of variables such as temperature, salinity, phytopigments, and oxygen concentration as well as ecological needs, including food acquisition, reproduction, or avoiding predators (Dietz, 1962) aggregating in moving deep scattering layers. Like their zooplanktonic prey, deep pelagic organisms are also known to vertically migrate, displacements known as diel vertical migrations (DVMs) when responding to a solar-based synchronization between the photic and aphotic realms (Brierly, 2014; Robinson et al., 2010), hence contributing to connectivity throughout the water column and supplying food to deep seafloor communities through the active downward transport of carbon and nutrients.

In the eastern Pacific, mesopelagic fish export about 15% of epipelagic carbon to deeper layers through their vertical migrations (Davison et al., 2013). Their daily mass migration also modifies fluxes of nutrients and oxygen (Robinson et al., 2010; Bianchi et al., 2013a, b) and helps support higher trophic levels across depths, including commercially important tunas and billfish, sharks, marine mammals, and small pelagic organisms (Potier et al., 2007; Johnson et al., 2011; Duffy et al., 2017), as well as benthic dwellers (Smith et al., 2008a, 2011). The eastern Pacific stands out in its proportion of vertically migrating fishes: strong differences have been observed, for instance, in the proportion of deep scattering layers migrating out of the mesopelagic at night, from 20% in the Indian Ocean to 90% in the eastern Pacific Ocean (Klevjer et al., 2016). The fish families Myctophidae and Gonostomatidae (Actinopterygii) dominate marine vertebrates caught in midwater trawls around the globe (Sutton et al., 2010) and account for a large portion of mesopelagic scattering layers (Perelman et al., 2021), including in the eastern Pacific.

Overall, two mesopelagic ecoregions have been delimited close to the CCZ with spatially distinct faunal assemblages (Sutton et al., 2017): the Northern Central Pacific (oligotrophic gyre, with different taxa compared to the equatorial Pacific) and the Eastern Tropical Pacific (eutrophic, with endemic taxa adapted to low oxygen).

3.5 Bioluminescence

Bioluminescence is considered to play an important role in deep-sea community structuration (Widder 2010; Haddock et al. 2017). Bioluminescence is used both for interspecific relations such as predation (Partridge & Douglas; 1995) and predation avoidance (Mensinger & Case, 1990; Robison, 1992; Pietsch, 2009). It also plays an essential role in intraspecific relations such as school formation, specific recognition, and matching for reproduction (Herring, 2007). Deep pelagic waters are characterized by a high level of transparency in most cases, wherefore bioluminescence is an effective means of communication that spreads over long distances, particularly in mesopelagic organisms (Johnsen et al., 2004; Claes et al., 2014a, b), given the highly developed visual systems observed in these organisms (Denton 1990; Warrant et al., 2003; Nilsson et al., 2012; de Busserolles et al., 2017).

In pelagic zones, it has been estimated that more than 75% of organisms are capable of emitting light (Martini & Haddock, 2017), while in the benthic zone, the number of bioluminescent species is estimated to be at least 50% (Martini et al., 2019). Diel vertical migrations (DVMs) of bioluminescent organisms also supply food to deep seafloor communities through the active downward transport of carbon and nutrients, thus playing a role in the benthopelagic coupling, a key factor to the ocean biological pump (Chatzievangelou et al., 2021).

3.6 Apex Predators and Other Charismatic Megafauna

The eastern Pacific is rich in Apex predators and charismatic megafauna, including blue and mako sharks or leatherback and logger head turtles, which have a widespread distribution and, as generalist meso-predators in oceanic food webs, are key components of pelagic communities and high sea ecosystems (IATTC, 2014) (Fig. 13.5). Several commercially important marine species such as billfish, tuna, sharks, larger squids, and rays regularly deep-dive into the meso- and even bathypelagic (1000–4000 m) layers (Thorold et al., 2014; Abascal et al., 2010; Fuller et al., 2015; Howey et al., 2016). In particular, key commercial species, such as yellowfin tuna, bigeye tuna, and swordfish, range to a depth of 1000 m, while species of cultural importance to Pacific Islanders, such as bottlenose whales or sperm whales, can reach 1500 and 3000 m depth, respectively (pilot whales and Cuvier's whales (*Ziphius cavirostris*) can also dive to 3000 m depth) (Fisheries and Aquaculture Department, 2000; Block et al., 2011; Schorr et al., 2014).

By the structure of their communities and the food webs they form, these Apex predators provide and sustain many of high-sea ecosystem services including provisioning, regulating, and cultural services (Juan-Jorda et al., 2015; Enquist et al., 2020). Specifically, tunas are known to move within the mixed layer during daytime but can descend below the mixed layer at night and will thus be directly impacted

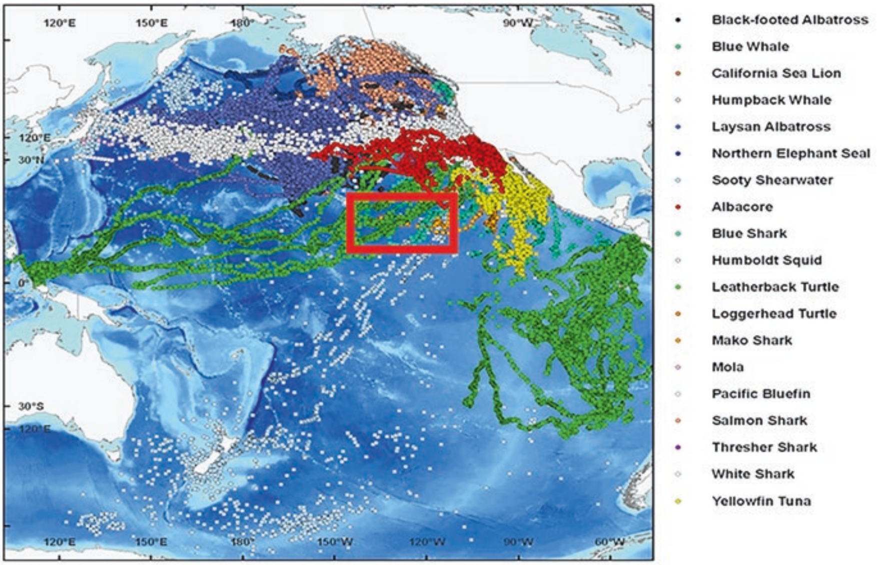

Fig. 13.5 Apex predators and charismatic megafauna tracks recorded monthly each year throughout the "Tagging of pelagic Predators' Program" (TOPP) in the Pacific (Costa et al., 2010). The CCZ is framed in red

by deep-sea mining activities if return waters are released in midwater layers (Schaefer et al., 2007).

The CCZ is also a major open ocean habitat for migratory marine species. Several whale species follow migratory routes through the CCZ to feed, driven by surface water temperature and primary productivity (Block et al., 2011; Tilot et al., 2023). Further, five sea turtle species are found in the CCZ, the olive ridley turtle (*Lepidochelys olivacea*) being the most abundant (Pitman, 1993) and the loggerhead (*Caretta caretta*), leatherback (*Dermochelys coriacea*), and green turtle (*Chelonia mydas*) classified as threatened (IUCN Red List—Polidoro et al., 2012).

Importantly, many of these Apex predators and marine megafauna can be considered ecosystem engineers, similar to zoo- and phytoplankton: they have lasting impacts on the trophic structure—keeping in check mid-size predators (Heithaus et al., 2008; Ritchie & Johnson, 2009; Ferretti et al., 2010; Ortuño Crespo & Dunn, 2017), which impacts phytoplankton growth and consequently geophysical parameters within the water column. For instance, sharks' and tunas' deep-dives for foraging and excretions in shallow waters contribute to upward nutrient shuttling (Thorold et al., 2014; Kiszka et al., 2015, 2022). Similarly, baleen and toothed whales are also considered ecosystem engineers or "whale pumps" because of their role in the upward nutrient pump and the deep sea ecosystems they sustain with their carcasses (Smith, 2006; Smith & Baco, 2003; Roman et al., 2014; Smith et al., 2014; Wang et al., 2021; Tilot et al., 2023).For example, annual Southern Ocean sperm whale faeces pump about 50 tonnes of iron ingested in deeper layers to the ocean surface

(Lavery et al., 2010). The iron contained in these faeces fosters phytoplankton growth, resulting in new primary production that fixes 200 000 tonnes of atmospheric carbon to the deep-sea annually (Lavery et al., 2010) – a necessary step in the absorption of greenhouse gasses, albeit insufficient to counter excess anthropogenic emissions globally (Meynecke et al., 2023).

Declining megafauna populations is linked to lower primary productivity because of lower upward nutrient cycling (Nicol et al., 2010; Roman & McCarthy, 2010) and changes in food-web structures and biogeochemical parameters (Lavery et al., 2010; Roman & McCarthy, 2010), resulting in overall decreased potential for organic carbon sequestration (Lavery et al., 2010; Pershing et al., 2010). The consequences of local declines in marine megafauna therefore extend much beyond the loss of culturally important species.

3.7 Interspecific Interactions

Interspecific interactions, mutualistic, antagonistic, or competitive, are important drivers of distribution patterns, local community assemblies, and evolutionary changes (Pantel et al., 2017). Several interspecific interactions occur in the CCZ. A tuna-dolphin-seabird interaction has been described in the eastern tropical Pacific region between 5°N and 30°N (Au & Perryman, 1985; Au & Pitman, 1986). Yellowfin tunas spotted (*Stenella attenuata*) and spinner (*Stenella longirostris*) dolphins drive small prey toward the surface, where boobies (*Sula* spp.), wedge-tailed shearwaters (*Puffinus pacificus*), jaegers (*Stercorarius* spp.), sooty terns (*Sterna fuscata*), and frigatebirds (*Fregata* spp.) forage on these preys. While this led to dolphins being recorded as bycatch in tuna fisheries, current changes in fishing practices are supporting an increase in dolphin populations (Ballance et al., 2021). Other interspecies interactions involve seabirds resting on sea turtles (e.g., boobies, black terns, and frigatebirds on olive ridley turtles) to reduce predation, to rest, and to feed on fish associated with the turtles (Pitman, 1993).

4 Deep-Sea Mining in the CCZ: Predicted Impacts on Marine Life and Human Activities

Areas of interest for the deep-sea mining industry can overlap with areas of interest for several other human activities (Fourchault et al., 2024). Related stressors, such as fishing, shipping, plastic pollution, and the suite of varying geochemical factors linked to climate change, are thus to be considered when evaluating synergies in negative anthropogenic impacts (Levin et al., 2018; Sharma, 2019; Ramirez-Llodra, 2020; Bell et al., 2021; van der Grient & Drazen, 2021) and incorporating ecosystem services into environmental management of deep-seabed mining (Le et al., 2017). Marine organisms in the water column of the eastern Pacific face cumulative stressors from diverse human activities, and especially fishing, in addition to the stressors inherent to deep-sea mining (Willett et al., 2006; Chang et al., 2012; Blanluet et al., 2023). The following paragraphs will highlight the foreseen impacts of deep-sea mining on pelagic organisms in addition to those reported in Drazen et al. (2020), followed by a brief description of cumulative stressors that may reinforce the impact of mining activities.

4.1 Predicted Impacts of DSM

DSM, in particular for polymetallic nodules, involves the exploration, extraction, transportation, and processing of minerals retrieved from the ocean floor and transiting through the water column to the surface before being shipped landwards. DSM is therefore tri-dimensional: ore is collected on the seabed, before being pumped upward through the water column as concentrated slurry (Fig. 13.6, adapted from Christiansen et al., 2020). This implies the release of a return plume, composed of seawater and low concentration seabed sediments, either at midwater or near the seabed before the ore is shipped to a terrestrial processing center (Miller et al., 2018).

Disturbances at the point of collection and return water outlet include sediment plumes that cause oxygen depletion, increased turbidity, possible dispersion of pathogenic material, and increased proportion of mineral particles, leading to nutritional deficiencies and repercussions at all trophic levels of the food web (for a full review, see Christiansen et al., 2020; Drazen et al., 2020). For example, suspension feeders, such as copepods, polychaetes, salps, and appendicularians forming an important basal group of the food web, may suffer from clogging of their mucous filter nets, resulting in death by starvation. Further, small particles may settle on gelatinous plankton, causing buoyancy issues. Bioluminescence processes by living organisms may also be hindered affecting communication and prey capture. Metals from crushed ore materials, including toxic elements, could enter the food web, bioaccumulate, and be released in the midwater and deep-sea ecosystems through carcasses.

Physical harm to living organisms through collisions, anthropogenic interference, and pollution will be caused by the increase in the number of vessels and operation platforms (Ritter & Panigada, 2019).

Consequently, DSM could result in increased mortality, altered migration patterns (both horizontal and vertical), decreased fitness, and shifts in community composition (Drazen et al., 2019).

Seabed collection and return water plumes will release sediments, the granulometry of which will determine their residence time in the water column. Discharge

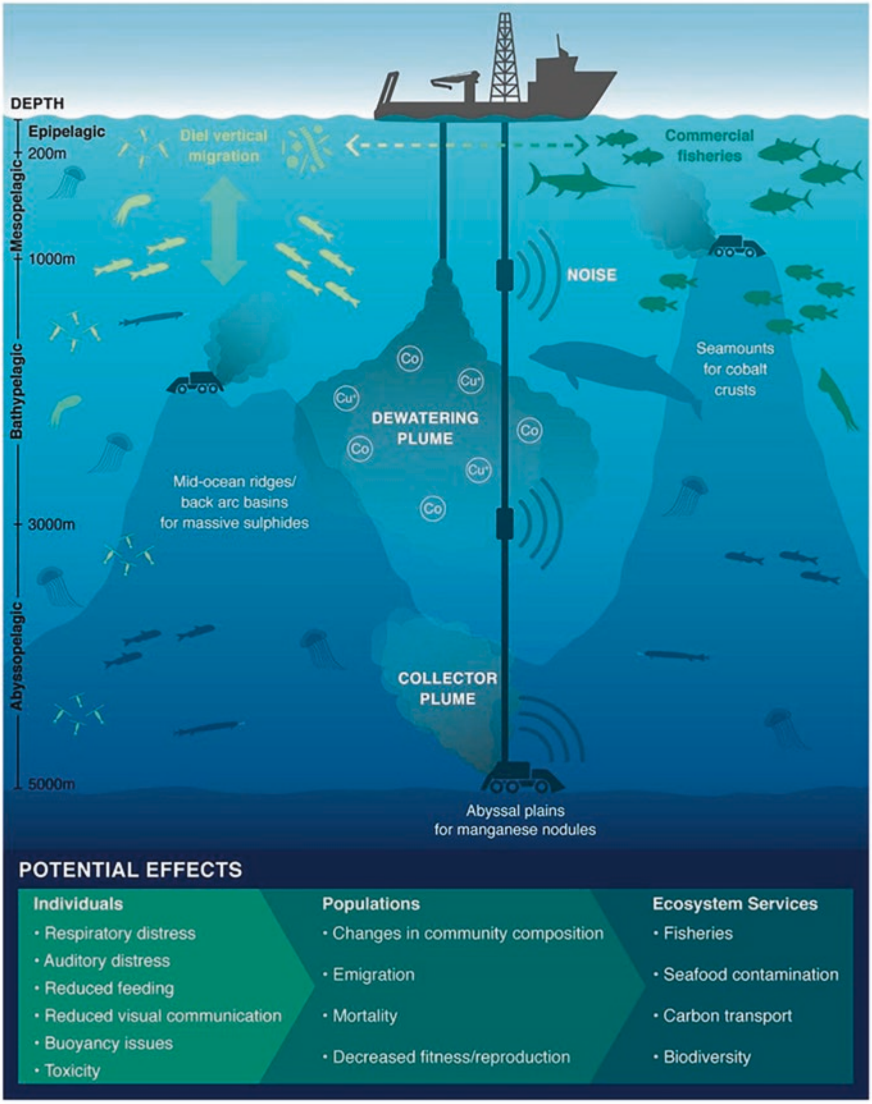

Fig. 13.6 Graphic representation of potential impacts from deep-sea mining (Reproduced from Drazen et al. 2020). Mining-generated sediment plumes and noise have a variety of possible effects on pelagic taxa. (Organisms and plume impacts are not to scale.) (Image credit: Amanda Dillon (graphic artist))

plumes in midwaters or at the seabed are estimated at 400 t day^{-1} dry solids suspended in about 50,000 t of water per collector (Christiansen et al., 2020). DSM dewatering discharge depth is a first key mitigation measure and should be below the mesopelagic/bathypelagic transition (i.e., below a depth of 1500–2000 m) to minimize impacts in the epipelagic (0–200 m) and mesopelagic (200–1000 m) zones, as these water layers are important for human food supply and other ecosystem services (Drazen et al., 2020).

The consequences in the euphotic and the aphotic zones will strongly impact mesopelagics that play a crucial role in the ocean biological pump with the transport of carbon and nutrients to the deeper pelagic and benthic realms (Christiansen et al., 2020; Drazen et al., 2020, Chatzievangelou et al., 2021).

To summarize, it is difficult to estimate the potential impacts of multiple mining operations over time and space with varying extracting and processing technologies, as there are considerable knowledge gaps regarding the possible long-term deleterious effects of deep seabed mining on deep-sea and open ocean ecosystems. Therefore, it is essential to better understand the unique habitats and associated faunal communities that are found in the CCZ and to quantify the crucial ecosystem functions and services they deliver (Glover & Smith, 2003; Thiel, 2003; Smith et al., 2008a; Tilot, 2010; Woodall et al., 2014; Levin et al., 2016, 2018; Le et al., 2017; Miller et al., 2018, 2021).

4.2 Deep-Sea Mining, Fishing, and Climate Change

As connections between the different layers of the ocean are better studied, there is growing evidence that both the water column and the seabed are affected by natural variations (seasonal climatic variation, El Niño events, benthic storms) and human activities (fishing, shipping, greenhouse gas emissions resulting in ocean acidification and changes in temperatures).

The fishing industry has become a major threat to pelagic organisms, which are increasingly exploited in response to depleted coastal stocks, growing fish-protein demand, the use of governmental subsidies, and technological innovation (Sumaila et al., 2015 in Van der Grient & Drazen, 2021; Ortuno Crespo & Dunn, 2017). Over the last seven decades, there has been a transition from large, long-lived, high trophic-level, piscivorous fish toward smaller, short-lived, low trophic-level invertebrates and planktivorous pelagic fish. Tunas and billfish stocks have declined by 60% on average in the last five decades, globally (Juan-Jorda et al., 2011).

Pacific Islanders are directly impacted by the diminishing trophic support of fisheries as they heavily rely on marine fisheries for protein and income (Johannes, 1987; Lieber, 1994; Rabbitt et al., 2019). The main tuna fishing activities globally occur within Pacific Island national waters, including waters of State Parties to the 1982 Nauru Agreement*, a regional cooperation with strong conservation benefits (Thakur, 1991; South et al., 2004). These provide 60% of the west and central Pacific Ocean tuna catch, and 25–30% of canned tuna worldwide, with a value of approx. USD 4.5 billion annually (Brouwer et al., 2018; The Western and Central Pacific Fisheries Commission, 2019).

(*The subregional Pacific Nauru Agreement concerning Cooperation in the Management of Fisheries of Common Interest was signed in 1982 between the

Federated States of Micronesia, Kiribati, the Marshall Islands, Nauru, Palau, Papua New Guinea, Solomon Islands, and Tuvalu. This agreement subsequently endorsed by the Western and Central Pacific Fisheries Commission includes presently all Distant-Water Fishing Nation fleets and coastal states that participate in the western and central Pacific tuna fisheries, the major commercial fisheries resource harvested in the Pacific (Thakur, 1991; South et al., 2004).)

Long-term datasets from the Pacific Ocean show that deep-sea communities are strongly affected by climate variation (Smith et al., 2009; Levin et al., 2018; Sharma, 2019), as are those of the upper ocean (Levitus et al., 2000; Barnett et al., 2005). For example, significant shifts in tuna biomass are likely to occur from west to east and from national jurisdictions to high seas (Bell et al., 2021), with a significant overlap of predicted tuna biomass distribution (both for skipjack, bigeye, and yellowfin species) and polymetallic nodule areas in the CCZ (Fig. 13.7). These stocks would therefore be under simultaneous pressure from the fishing and the deep-sea mining industries (van der Grient & Drazen, 2021) that would cause a reduction in the provisioning of commercial fish species and biomass and an increase in toxic metals throughout pelagic food webs and hence seafood supply (Drazen et al., 2019).

This would affect the eastern Pacific where at least ten countries derive 10% or more of their regional fisheries management organization from areas overlapping with mining areas (WCPFC, 2019; Van der Grient & Drazen, 2021).

More specifically in the CCZ, anthropogenic and climate change disturbances have been evidenced with two areas of high bycatch estimates in international waters near Hawai'i and Mexico (Halpern et al., 2013, 2015).

Mitigating the cumulative impacts of industrial fishing and deep-sea mining on pelagic fisheries will thus be essential to safeguard economically important fishing activities and to ensure food safety. In this perspective, the ISA suggests that several priority areas for research and monitoring should be designated in the CCZ (ISA, 2023). Currently, several global ocean models are available at the spatial resolution needed to better understand the deep-sea mining interactions with fisheries (Fagundes et al. 2020; Ringler et al. 2013; Xiao et al., 2022).

4.3 Deep-Sea Mining and Shipping

The mining of polymetallic nodules in the CCZ will result in higher shipping densities above the relatively unvisited surface waters of the CCZ and across the Pacific to transport the ore for on-land processing. Consequently, the risk of collision, anthropogenic interference, and pollution with megafauna will increase (Ritter & Panigada, 2019). Further, the noise and light emitted by these ships will further influence the behavior of marine fauna relying on physical cues for orientation and communication. Auditory masking will likely occur in the epipelagic layer, with surface support vessels producing low frequency and broadband sound similar to frequencies emitted by commercial shipping vessels (Thompson et al., 2023). Throughout the water column, further auditory masking is linked with acoustic

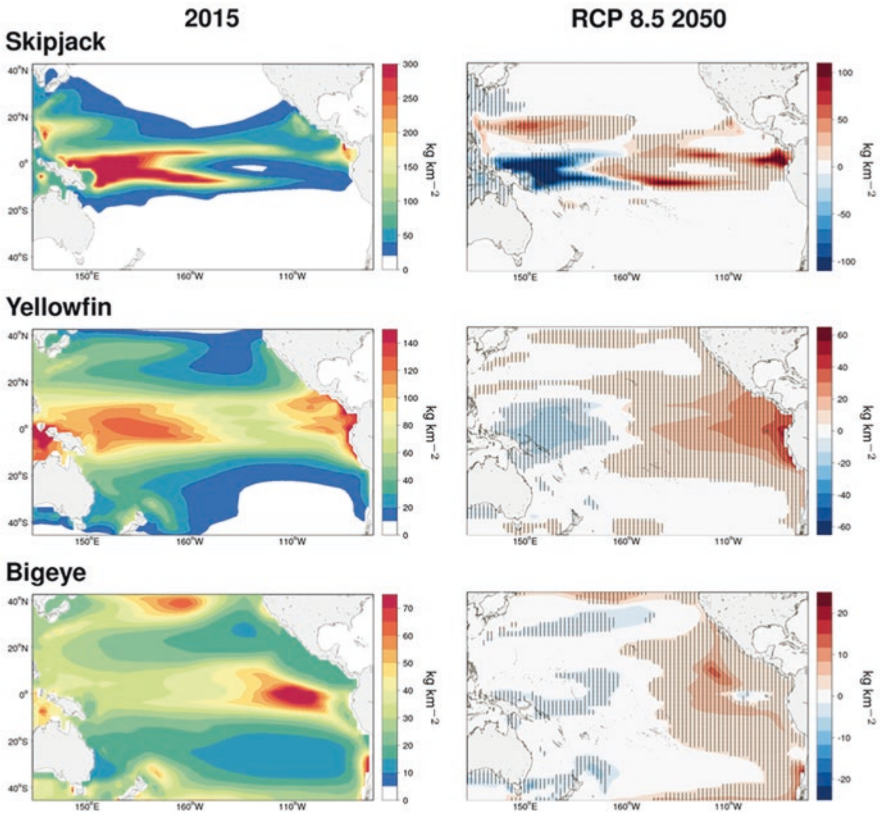

Fig. 13.7 Predicted shifts in tuna biomass distributions (Bell et al., 2021). Average biomass distributions (kg km^{-2}) of skipjack, yellowfin, and bigeye tuna in the Pacific Ocean basin for 2015 (2011–2020) (left) and mean anomalies (kg km^{-2}) from the average 2015 biomass distribution of each tuna species projected to occur by 2050 (2044–2053) under the RCP 8.5 greenhouse gas emissions scenario (right). Shading indicates areas where projections from four Earth System Models agree in the sign of change

telemetry for remotely operated vehicles, which overlaps with Delphinidae and Odontoceti clicks, and dredging noise, which overlaps with the wavelengths of both small (e.g., humpback whales) and larger (e.g., blue whales) Mysticeti (Thompson et al., 2023, and references therein).

Finally, cumulative impacts would occur by the fact that navigational routes cross the CCZClarion Clipperton zone (CCZ) area. In particular in the southern part of the CCZ, busy shipping lanes link the Panama Canal with east Asia and in the North and East (Schwer & McGillivary, 2007; Halpern et al., 2013, 2015; Avila et al., 2018; Tilot et al., 2023).

5 DSM and Ecosystem Services of the Pelagic Ecosystems

Ecosystem services are the products of healthy, diverse, and functioning ecosystems and their.

associated living organisms, which contribute to human well-being (Rogers et al. 2014). The high seas, in particular, are known to provide several key ecosystem services (Fig. 13.8) that benefit human societies (Armstrong et al., 2012; Santora et al., 2021; Xuan et al., 2021; La Bianca et al., 2023):

- Existence and stewardship values of all organisms.
- Supporting services (e.g., biomass production, geochemical cycling, habitat provision).
- Provisioning services (e.g., halieutic resources, raw materials and genetic resources for pharmaceutical or other industrial applications). Examples of raw materials include fisheries (Victorero et al., 2018) and deep-sea minerals (Thurber et al., 2014). Examples of genetic resources include bamboo corals that are used as a model for synthetic human bone replacements (Ehrlich et al., 2006) and sponge spicules that are superconductors for light (Brummer et al., 2008). Deep-sea sponges and associated microorganisms are also a source of bioactive metabolites for pharmaceutical applications such as anti-tumor, antibacterial, antiviral, toxin inhibitors, and anti-inflammatory metabolites (Rateb & Ebel, 2011; Batista-Garcıá et al., 2017; Koch et al., 2021).
- Regulating services (e.g., climate regulation, nutrient cycling, waste treatment). In the context of climate change, the finding of the role of whale-fall ecosystems in carbon sequestration is of importance (Smith et al., 2014). In the same perspective, deep demosponges have a role in filtering out bacteria and dissolved

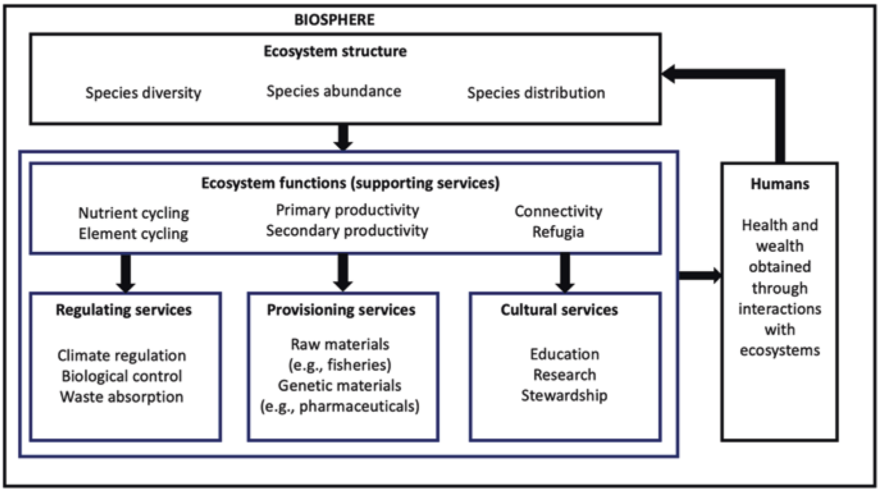

Fig. 13.8 Key services provided by healthy high seas ecosystems for human well-being

organic carbon from seawater (Kutti et al., 2013; Cathalot et al., 2015; Leys et al., 2018).
– Cultural, artistic, educational, and scientific services (e.g., information for research, education, leisure, inspiration for culture, art, and design) (Turner et al., 2020).

So far, only a few attempts have been made to quantify marine ecosystem services (Sumaila et al., 2007, 2015; White & Costello, 2014). La Bianca et al. (2023) highlight the importance of valuing supporting services, which have been neglected in recent studies. Indeed, studies more frequently quantify provisioning services, as these directly benefit commercial activities. Nonetheless, to identify the importance of an ecosystem for fish and invertebrate catch, the number and volume of breeding or spawning grounds, the nursery habitat(s), and the primary production for trophic support—which are all supporting services—need to be evaluated (Le et al., 2017; La Bianca et al., 2023). Other ecosystem functions, such as survival and recruitment rates and larvae and juvenile populations' linkage to adult populations, are also key to apply economic value to an ecosystem (Le et al., 2017). Similarly, among regulating services, carbon sequestration is relatively better studied and is known to depend on functions such as primary productivity at the surface, carbon flux to the bottom, and degradation and burial rates of organic carbon (Smith et al., 2015a, b).

Generating and merging the economic values of all services provided by ecosystems found throughout the water column above mining sites is therefore a complex but necessary task, which will allow to balance the costs and benefits of conserving habitats and wildlife (Jobstvogt et al., 2014; Fourchault et al., 2024).

Deep-sea mining activities will impact ecosystem services provided by benthic, demersal, and pelagic organisms living near or migrating close to commercially interesting mineral deposits (Glover & Smith, 2003; Drazen et al., 2020; La Bianca et al., 2023). Industrial deep-sea mining processes will have various ecological consequences, which will impact the health of marine organisms and the quality of the ecosystem services they provide (Table 13.1). Even the earliest mining activity would have an environmental impact at a regional scale, disturbing ecosystems both on collected sites of the benthos and in the water column, surface, and above mined sites. Impacts in larger areas would depend on oceanographic and atmospheric processes occurring in the area (Glover & Smith, 2003; Drazen et al., 2020).

We thus need standardized procedures both to understand the mining-induced consequences on ecosystem structures (Van Dover et al., 2017; Niner et al., 2018) and to gain knowledge on how changes in ecosystem structures will impact ecosystem functions and services (Ginzky et al., 2020).

Table 13.1 Potential impacts of deep-sea mining on ecosystem services throughout the water column

Industrial process	Ecological consequences	Impacted organisms	Impacted ecosystem services
Ore collection	Sediment compaction Habitat alteration Increased turbidity Light pollution Sound pollution Accidental release of chemicals	Benthic and demersal species: negatively impacted respiratory systems, feeding efficiency, behaviour, growth, reproduction, mortality (e.g., Christiansen et al., 2020)	***Supporting services*** Habitat provision (e.g., diminished breeding grounds and refugia) Biomass production (through disrupted trophic chains) ***Regulating services*** Climate regulation (e.g., lower carbon sequestration because of lower biomass levels; lower carbon capture from lower phytoplankton growth because of reduced upward nutrient shuttling from deep-diving predators; increased turbidity negatively impacting carbon fixation by mesopelagics) (but see Orcutt et al., 2020) Biological control and waste treatment (e.g., reduced filtration of bacteria and dissolved organic carbon through deep sponges) ***Provisioning services*** Genetic resources (e.g., fewer biomaterials, pharmaceuticals, industrial agents) Trophic support for fisheries (e.g., reduced feeding efficiency of tuna, swordfish, squid, and depletion of slow-growth deep-sea fisheries) Geochemical cycling (e.g., lower upward nutrient shuttling through dial vertical migration, deep-diving predators, or marine mammals) ***Cultural services*** Historical archives (e.g., destruction of fossils records in sediments) Research and education Stewardship and bequest value Outreach value attached to marine mammals and deep-sea octopus (Tilot et al., 2021b) ***Existence and stewardship value services***
Pumping of ore through riser systems	Removal of ambient water Noise pollution Potential accidental leaks leading to sediment plumes	Benthic and demersal species: negatively impacted larval dispersal (Christiansen et al., 2020) Marine mammals and species relying on sound: negatively impacted communication, behaviour, reproduction, growth (Thompson et al., 2023)	
Release of return water through discharge systems	Sediment plumes leading to increased turbidity, release of chemicals and biohazards Cold, slightly saltier water release	Mid-water organisms: negatively impacted feeding efficiency, respiratory processes, behaviour, and reproduction (e.g., Haddock et al., 2017)	
Production support vessels	Noise pollution Light pollution Collision risk	Epipelagic organisms, including marine mammals (e.g., Thompson et al., 2023) Mid-water and deep pelagics relying on trophic input from upper layers (Drazen et al., 2020)	

6 Conservation and Sustainable Management Strategies

6.1 Different Options for Managing Conservation and Sustainable Development in the High Seas and in the CCZ

Customary marine resource management incorporating traditional knowledge and beliefs have long been practiced in the Pacific to conserve and manage sustainably marine areas and species (https://www.sprep.org). These managed areas are now called "Locally Managed Marine Areas" (LMMAs) and are part of a network shared by Fiji, Papua New Guinea, and other islands (https://www.lmmanetwork.org). A portion of the fishing grounds is usually set aside as a no-fishing zone to safeguard the future sustainability of fisheries resources (Tawake 2004; Veitayaki et al., 2003). The success of each area in the network is measured by the health of the ecosystem, habitats, and species, along with the reduction of threats and the well-being of people who use the resources (Tawake & Tuivanuavou, 2004).

It is now widely accepted that as a science-based tool of conservation, Marine Protected Areas (MPAs) are particularly effective and serve as enforceable tools to safeguard marine biodiversity from trophic downgrading on the oceans (Estes et al., 2011; Jeudy de Grissac, 2015) and from deleterious impacts from anthropogenic activities (Agardy, 1994; Margules & Pressey, 2000; Roberts et al., 2001; Edgar et al., 2007; Gaines et al., 2010; Halpern et al., 2010; Duarte et al., 2020).

The numbers and extent of MPAs have increased steadily and more substantially in recent years with the adoption by the United Nations Convention on Biological Diversity (CBD) of a new target at the horizon 2030, the 30 × 30 proposal, increasing the effective conservation target to at least 30% of the world's lands, inland waters, coastal areas, and oceans, with emphasis on areas of particular importance for biodiversity and ecosystem functioning and services. In particular, the CBD recommends prioritizing ecologically representative, well-connected, and equitably-governed systems of protected areas and other effective area-based conservation, recognizing indigenous and traditional territories and practices, which directly addresses the situation of managing human activities in the high seas (https://www.cbd.int/article/draft-1-global-biodiversity-framework).

Therefore, there is an increased interest toward finding strategies that synergize conservation and exploitation of marine ecosystems and resources (Kriegl et al., 2021). An ongoing multidisciplinary consensus stresses the importance of MPAs promoting ecosystem resilience (Peterson et al., 1998; Folke et al., 2004) and rebuilding life in the ocean (Duarte et al., 2020) and as "key components of global marine conservation strategies" (Lubchenco et al., 2003; Gaines et al., 2010; McCrea-Stub et al., 2011).

Recognizing the importance and value of deep-sea ecosystems and the biodiversity they contain, the United Nations General Assembly (UNGA) resolution 61/105 in 2006 called "upon States to take action immediately, individually, and through regional fisheries management organizations and arrangements, and consistent with the precautionary approach and ecosystem approaches, to sustainably manage fish stocks and protect Vulnerable Marine Ecosystems (VMEs), including seamounts (Clark et al., 2011, 2016), hydrothermal vents and cold water corals, from destructive fishing practices" (https://www.fao.org/in-action/vulnerable-marine-ecosystems).

Presently, VMEs target areas could be extended to areas that would be impacted from other human activities, such as deep-sea mining.

In 2008, a process was put in place by the CBD, to recognize « Ecologically and Biologically Significant Areas (EBSAs) » on seven scientific criteria: uniqueness or rarity, special importance for life stages of species, importance for threatened, endangered, or declining species and/or habitats, vulnerability, fragility, sensitivity or slow recover, biological productivity, biological diversity, and naturalness (https://www.cbd.int/ebsa).

The International Maritime Organization (IMO) has adopted the Resolution A.720 (17) concerning guidelines for the identification and designation of Particularly Sensitive Sea Areas (PSSAs) for species, habitats, and seascapes and has established special protective measures that ships must follow. IMO's PSSA program supports the UN Sustainable Development Goal 14 to conserve and sustainably use the oceans, seas, and marine resources for sustainable development. It also supports other protective measures and mechanisms, such as the UNESCO World Heritage Marine Sites, and Ecologically or Biologically Sensitive Areas under the Convention on Biological Diversity. So far, 15 PSSAs in the world have been identified and designated. For the Pacific, they include the Great Barrier Reef.

Other Effective Area-Based Conservation Measures (OECMs) allow to achieve conservation objectives mainly as a by-product of other management strategies. These are geographically defined and governed and managed in ways that achieve positive and sustained long-term outcomes for in situ conservation of biodiversity, with associated ecosystem functions and services including cultural, spiritual, socio-economic, and other locally relevant values (https://biodiversity.europa.eu/europes-biodiversity/protected-areas/other-effective-area-based-conservation-measures).

The emerging internationally legally binding instrument under the auspices of the United Nations for the conservation and sustainable use of marine biodiversity from the seafloor to the surface is the new UN agreement on Biodiversity Beyond National Jurisdiction (BBNJ), or the BBNJ Treaty, adopted by the UN, June 19, 2023. Its role is « to ensure the long-term conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction through effective implementation of the relevant provisions of the Convention and further international cooperation and coordination ». "The common set of overarching goals and objectives of the BBNJ to ensure the ecological integrity of ocean ecosystems (Kim & Bosselmann, 2015; Kim & van Asselt, 2016) are the following:

- Marine genetic resources, including the sharing of benefits.
- Area-based management tools, including MPAs.
- Environmental impact assessments.

– Capacity-building and transfer of marine technology" (https://www.un.org/bbnj).

In the Areas Beyond National Jurisdiction (ABNJ), the importance of protecting and conserving natural resources and ecosystems is outlined as ecosystems are ecologically closely interconnected. However, it lacks a coherent and holistic governance based on precaution and knowledge-based decisions (Gjerde & Yadav, 2017; Gjerde et al., 2019).

The concept of ecosystem-based management (EBM) provides the basis for more coordinated, holistic, and transboundary governance of interrelated areas of the ocean that are politically divided, such as the High Seas and the Area in ABNJ (De Lucia, 2019; Gjerde & Wright, 2019; Tunnicliffe et al., 2020; Warner, 2016; Tilot, 2023).

– "Oceanic Marine Protected Areas" (OMPAs) (defined here as waters >200 m depth) have emerged from the ratification of the BBNJ Treaty (Blanluet et al., 2023).
– "Large Marine Protected Areas" (LMPAs) (defined for areas >100,000 km^2) have been created in the current decade, often in networks (Corrigan & Kershaw, 2008; Game et al., 2009; O'Leary et al., 2012; Gianni et al., 2016). With LMPAs, all natural processes and habitats, including deep sea and deep-sea habitats, are protected. Evidence has shown that LMPAs are much more cost-effective to implement and manage as smaller MPAs, especially when including corridors for migrating species (McCrea-Stroub et al., 2011), particularly with the ratification of the BBNJ Treaty.

Concerning the CCZ, two large EBSAs are bordering the CCZ to the north and the south: (1) the North Pacific Transition Zone, bounded to thermohaline fronts and eddies, a highly productive habitat and migratory corridor for many pelagic predators including endangered and commercially important species (2) and the Equatorial High-Productivity Zone, a large-scale oceanic feature supporting high primary production over a large area and a strong benthic-pelagic coupling strongly related to surface primary productivity. Both EBSAs are rated "high" for uniqueness, due to their large scale as well as being major components of the oceanographic processes within the Pacific Ocean; they are also rated as "high" for primary productivity (https://www.cbd.int/ebsa).

The CCZ also includes several Important Bird Areas (IBAs), in particular for petrels and shearwaters, and Important Marine Mammal Areas (IMMAs). The area is also under the influences of the Clipperton Fracture Zone Petrel foraging area, the Clipperton Atoll, a highly endemic habitat and an outpost for the migratory flux coming from the west, and the North-East Pacific White Shark Offshore Aggregation Area. Evidence has shown as well that, unrelated to geographic distance, coastal regions are connected to ABNJ, such as the CCZ, both through larval dispersal and through the potential dispersal of pollutants (Popova et al., 2019).

In the CCZ, the recognition of marine protected areas "where sea-floor mining and other deleterious activities are not allowed" is considered impracticable. Instead, the International Seabed Authority (ISA) has designated thirteen "Areas of Particular

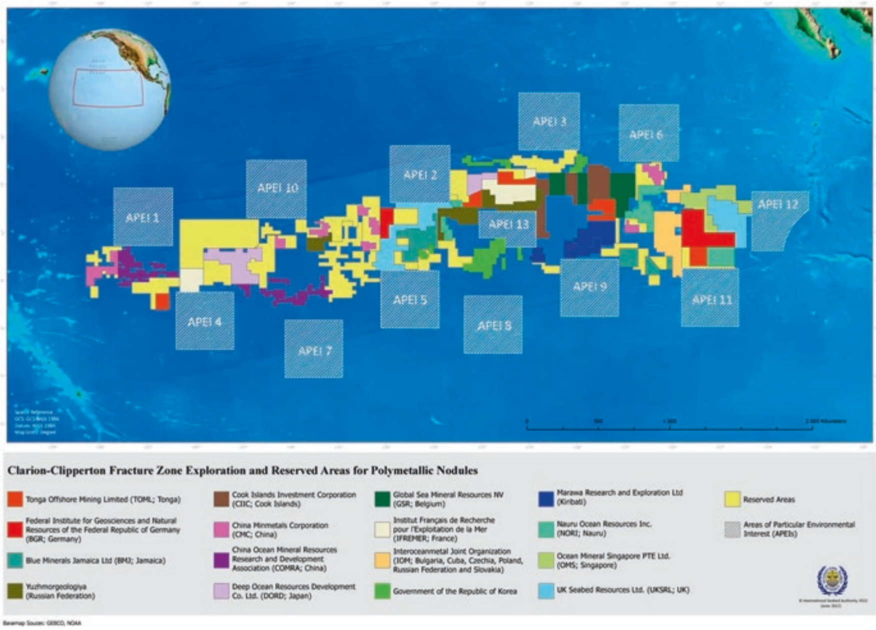

Fig. 13.9 Exploration Area and the thirteen Reserved Areas (APEIs) for polymetallic nodules in the Clarion-Clipperton Fracture Zone. (https://www.isa.org.jm/maps/clarion-clipperton-fracture-zone/)

Environmental Interest (APEI)," or "Impact Reference Zones," or "Preservation Reference Zones" (Smith et al., 2008b; Wedding et al., 2015), the purposes of which would be to assist the ISA in taking decisions concerning the modalities of nodule exploitation and its impact both on the ecosystems concerned and on the future of mining activities (Fig. 13.9).

In order to serve as valid reference sites, these APEIs should be fully representative of the areas to be exploited in terms of depth, physical and chemical nature of the substratum, associated faunal communities and ecosystems, overlying chemistry and oceanography of the water column, and broader climatology, all of which ideally require monitoring at different temporal and spatial scales (Freiwald & Roberts, 2006; Tilot, 2010; Oesterwind et al., 2016; Tilot et al., 2018). They would also need to remain effectively unimpacted and to have extensive buffer zones, as generally have other MPAs, especially in the high seas.

However, these conditions are not entirely respected as some APEIs are not fully representative of the mining sites, with some containing other habitats, such as seamounts, than those targeted by nodule mining (Tilot, 2010; Tilot et al., 2018; Jones et al., 2021). APEIs may nonetheless be impacted by the plumes deriving from the mining technology that would occur throughout the whole water column. As well according to the topography, the oceanographic processes and associated life cycles, plumes may adopt several patterns and travel over great distances (Weaver et al., 2022).

The APEI network, presently designed only for reference purposes, should thus be associated with management activities to help mitigate the impacts of mining in the CCZ (Tilot, 2010; Tilot et al., 2018; Kriegl et al., 2021). A network of flexible MPAs, preferably linked to tridimensional LMPAs, with corridors and buffer zones and expandable boundaries, would be the best option (Tilot et al., 2023).

ISA has been developing Regional Environmental Management Plans (REMPs): *a proactive area-based management tool to support informed decision-making that balances resource development with conservation* (ISA, 2018, 2020). ISA also considers the potential interactions between fishing and mineral resource-related activities in areas ABNJ with a spatial analysis (ISA, 2023).

If designed as a legally binding instrument, REMPs would allow the ISA to function as a proper regulator, i.e., through feedback of REMP cumulative environmental assessments on regional ISA contracting and the respective environmental standards for activities (Jaekel, 2016), including Best Environmental Practice and the use of Best Available Technologies. The regional level may be best suited to set precautionary thresholds for "effective protection," "harmful effects," and "serious harm," identify the appropriate indicators for a regional monitoring program, and carry out the necessary environmental assessments that leads to an integrated management and embrace reviews in an adaptive review cycle.

The newly adopted High Seas Treaty could provide a critical impetus to secure the necessary strategic perspective of marine spatial planning for integrating sectoral management tools such as the ISA REMPs into the global biodiversity conservation agenda in ABNJ with EBSAs, VMEs, IMMAs, LMPAs, PSSAs, and OECMs in relation to risks from mining-related activities as all ecosystems in the high seas are closely interconnected (Ardron et al., 2008; Maes, 2008; Tilot, 2010).

6.2 Deep-Sea Mining and Traditional and Cultural Dimension in Managing Marine Resources

Pacific Islanders, in particular Indigenous Peoples and Local Communities (IPLCs), embrace their role as custodians of ecosystems and of species, which they perceive as interconnected. IPLCs are particularly attached to migratory species and traditional navigation routes in the open Ocean (Johannes, 1981; D'Arcy, 2006; Ey & Sherval, 2016; Eckstein & Schwarz, 2019). Similar to the sensory navigation used by sea turtles, sharks, and whales, Pacific Islanders practice the traditional art of navigating, using the motion of stars, the shape of clouds, the color of the sea, the movements of marine species, the shape of waves, currents, and water temperature (Lohmann et al., 2008), envisioning the Pacific as a "Sea of Islands" (Hau'ofa, 1994, 2008). Deep-sea mining activities therefore cannot be conceptualized as being far off, or beyond Pacific Islanders' territories, despite their location outside of official national boundaries.

Traditional knowledge and customary practices have long been practiced in the Pacific to conserve and manage sustainably marine areas and species (https://www.sprep.org). Presently called LMMAs, as described previously, they form a network (https://www.lmmanetwork.org).

There is a long-standing call of civil society of the Pacific Island Countries to preserve the marine environment and the resources and to prioritize the health and values of Pacific communities, in particular traditional knowledge, e.g.,10 year moratorium on DSM from 2020 to 2030 to allow for prudent research in marine areas under national jurisdiction of the Pacific nations (Fiji, PNG, Vanuatu, Cook). The Cook islands has incorporated traditional practices such as the "rahui" in its strategy of ocean governance over its extended EEZ (Govan et al., 2009). The "rahui" is a complex system of rules and prohibitions regulating interactions between specific peoples and organisms (Bambridge, 2016). The subregional Pacific Nauru Agreement (PNA) concerning Cooperation in the Management of Fisheries of Common Interest signed in 1982 outlines strong conservation benefits in the region (Tilot et al., 2021a). The traditional and cultural dimension of Pacific Island Countries is also taken in account in the recent agreement on Biodiversity Beyond National Jurisdiction (https://www.un.org.bbnj).

Most Pacific Islands countries have ratified or acceded to global, regional, or sectoral instruments relevant to ensuring the protection of the marine environment and biodiversity or more exactly "the protection of living things, their physical environment and/or the ways in which holders of traditional knowledge utilize them for maintaining, facilitating, or improving human life" that would be impacted by DSM activities, such as with the CBD in 1992, the Madang Guidelines on Principles for the Development of National Offshore Mineral Policies in 1999 (https://pacific-data.sprep.org/dataset/madang-guidelines-principles-development-national-offshore-mineral-policies), and the Noumea Convention for the Protection of Natural Resources and the Environment of the South Pacific Region in 1986 which contains an indirect reference to the cultural value of areas and the exercise of traditional customary rights in one of its protocols (https://www.sprep.org/convention-secretariat/noumea-convention) (Tilot et al., 2021a). There is also "the Pacific Plan for strengthening Regional Cooperation and Integration" with a strategic framework of regional policies, approved by the Pacific Islands Forum leaders in 2005 (https://www.pacificplan.org).

Traditional dimensions of seabed resource management are clearly integrated in the national laws in some countries, such as for the Cook Islands with its LMPA, vast multipurpose MPA, covering their entire territorial sea and exclusive economic zone which encompasses a huge share of the world's currently known cobalt (Cook Islands Marae Moana (=sacred ocean) Act 2017). In this perspective, the Cook Islands, using the traditional "rahui" concept, balance the economic interests like tourism, fishing, and deep-sea mining with conserving marine biodiversity and ecology, in order to maximize the benefits for the current and future generations of the Islanders (Willaert, 2020; Tilot et al., 2021a).

LMPAs offer unique opportunities to protect also cultural seascapes and to enable indigenous communities to maintain their traditional practices while participating in management (Bambridge & d'Arcy, 2014; Lewis et al., 2017). North of the CCZ, the Hawaiian marine national monument, Papahanaumokuakea, a very large marine protected area of 1.508870 km^2 and World Heritage site, was created in particular for biocultural reasons.

6.3 *Proposed Marine Spatial Planning and Management Tools in the CCZ*

Marine spatial planning in the high seas and deep sea needs to pursue an integrated approach that considers transparency and all stakeholders and sectors of activity and fully appreciates the tridimensional status of the oceans, in conformity with the principle of the ecosystem approach to management (EAM), and the commitments enshrined in the Convention on Biological Diversity health (https://cbd.int/ecosystem), (Tilot, 2004; Ardron et al., 2008; Cormier et al., 2017, 2019; Brito-Morales et al., 2022; Fourchault et al., 2024).

An example of an application of a strategic approach to marine spatial planning based on EAM is the marine mammal sanctuary "Pelagos" shared by three countries in an upwelling area of importance for cetacean in the Mediterranean Sea (Tilot, 2004; Ardron et al., 2008). The "Pelagos" agreement is looking at the reduction of all potential impacts on cetaceans, including pollution, navigation, nautical tourism, whale watching, and noise, and adopts necessary regulations related to the surface of the sea, the water column, and the sea bottom.

Concerning the management of a vast area in the high seas targeted by DSM, such as the CCZ, the marine spatial planning strategy would require a comprehensive assessment of baseline environmental and oceanographic parameters and of ecosystems as well as of natural, anthropic and cumulative impacts. This comprehensive assessment should be performed at temporal and spatial scales (Ardron et al., 2008; Foley et al., 2010). Marine spatial planning is generally executed through a Transboundary Diagnostic Analysis (TDA) and then a Strategic Environmental Assessment (SEA) in ocean governance (Gjerde & Yadav, 2017).

Because pelagic ecosystems are dynamic with vertical and horizontal migrations, and because mining effects are probably drifting as well, a Lagrangian (drifting) perspective is needed in monitoring and management. Consequently, potential broad-scale impacts to pelagic ecosystems should be considered with the choice of stations for environmental baseline and monitoring studies and other area-based management and conservation measures, in particular the choice of APEIs (Drazen et al., 2019) and possibly oMPAs, as highlighted above. Also, management systems should incorporate elements of adaptive or reactive management, so that preventive action can be taken as soon as new information becomes available (Cormier et al., 2017).

6.3.1 Metrics for Biodiversity Assessments, Ecosystem Dynamics, and State of Health

Key water column parameters further include turbidity, current speed, dissolved oxygen concentration, primary production, and alkalinity. Most of these variables can be measured with sensors, such as lowered acoustic Doppler current profilers (LADCPs) for current velocity.

Concerning taxonomic diversity measures of biodiversity, at both within-habitat and within-region scales, it is a priority to develop metrics, adapted to assess and monitor ecosystems where full species and habitats lists are unavailable as in the high seas, in particular in the CCZ (Warwick & Clarke, 2001; Gray, 1997; Price, 1999; Izsak & Price, 2001), as well as process-oriented metrics that account for ecosystem dynamics across temporal and spatial scales (Steneck, 2001; Price et al., 2007). Key functional groups, ecological roles, and species interactions (Hughes et al., 2005) can be assessed by measures that are not too sensitive to sample size such as average taxonomic distinctiveness (i.e., a measure of the mean taxonomic distance between species within a sample or study area) and variation in taxonomic distinctiveness (i.e., a measure of the variance in taxonomic distance between species) (Warwick & Clarke, 2001). Complementing taxonomic distinctiveness, the concept of taxonomic similarity (i.e., the mean taxonomic distance between species from different samples or sites), would enable comparison across areas at different scales being not too sensitive to sampling intensity (Izsak & Price, 2001; Price, 2002; Price & Izsak, 2005).

Further, diversity indices, such as Environmental Sensitivity or Vulnerability Indices, can be used to prioritize different conservation areas. These indices are often coupled to Geographic Information System (GIS) to indicate biological sensitivity to different classes of impact and the likelihood of occurrence of these impacts (Cogan et al., 2009). ESI maps have been widely applied to the marine environment, first for risk management of spills in the oil industry (Buckley, 1982; Tortell, 1992; Jensen et al., 1993). ESI maps, when complemented by maps representing socio-economic data, can sharpen the collaboration between managers and stakeholders to identify vulnerable locations, establish protection priorities, and identify strategies to minimize undesirable consequences. The value of habitats as surrogates for ecosystem services needs further consideration, as there can be important co-benefits or opportunity costs associated with either their conservation or their loss (Fraschetti, 2012; Fourchault et al., 2024).

6.3.2 Reference Levels and Alert Systems for Spatial Marine Management

The establishment of reference levels on which management decisions can be made and clear protocols to evaluate trade-offs (Link & Browman, 2017) are needed for the spatial planning and management of the CCZ. Alert systems, in contrast, are still novel in their application to marine areas, but have, for example, been proposed in relation to coastal areas and MPAs in the Red Sea, Gulf of Oman, and Arabian Gulf

(Tilot, 2016; IUCN/ROWA, 2016). Levels of key biological (e.g., live coral cover) or physical (e.g., sediment load) or chemical (e.g., oil hydrocarbon) parameters are set to trigger management action to halt the damaging activity, such as an oil leak and implement restitution activities (e.g., oil spill clear up) as previously determined. Often, alert systems discriminate more than one threshold, using a traffic lights system (Halliday et al., 2001; Ceriola et al., 2007; Barange et al., 2010).

6.3.3 Rapid Environmental Assessment and Other Monitoring Techniques

The need for marine biological observations and monitoring strategies to inform science, early warnings, climate projections, protect ocean health, and support the blue economy leads to the identification "Essential Ocean Variables (OEVs)" by the Global Ocean Observing System (GOOS) expert panels (https://goosocean.org/what-we-do/framework/essential-ocean-variables/) (Estes et al., 2021).

Ecosystem surveys or holistic monitoring, in particular when combined with numerical modeling, have proven to be more efficient to resolve ecosystem status and changes in the full temporal and spatial domains, but to obtain higher precision for some stock estimations, there will always be a need for single species/group surveys (Eriksen et al., 2018).

Concerning the design and location of newly declared oceanic MPAs (oMPAs), as described previously, new sampling platforms and methods will serve to best protect biodiversity across the water column (Blanluet et al., 2023). Indeed, clear and measurable conservation objectives and management targets have to be set and evaluated within solid monitoring schemes. The design of a clearly structured evaluation framework, similar to the drivers-pressures-state-impact-response framework (DPSIR), may support this process (e.g., Gabrielsen & Bosch, 2003; Oesterwind et al., 2016).

Rapid environmental (or ecological) assessment (REA) has been developed, typically for the assessment of large areas (Price, 1999; Tilot, 2014). REAs have in common that they accept semi-quantitative abundance estimates of biological taxa and of environmental factors, often assessed on a predefined (often 5- or 6-, or 10-point) scale (Tait & Dipper, 1998). Further, in order to assess the diversity or monitor the presence of keystone trophic groups, REAs restrict species identification to preselected orders or families, for example, echinoderms or fish (Hourigan et al., 1988; Roberts et al., 1988; Montevecchi, 1993; Whitfield & Elliott, 2002; Price, 2004). While individual estimates may lack precision, statistical methods can be applied to the data, enabling quantitative conclusions. Subsequent refinement for specific areas or taxa can then be obtained through archived imagery or additional genetic or tag-based studies.

The moving vessel profiler (MVP) is a rapid assessment tool for the collection of water column profiles and sediment classification used in the water column (Paka et al., 2020). It has been effectively used to collect mid-water oceanographic information to support science and hydrography survey operations.

The use of productivity and susceptibility analysis (PSA) and a rapid management-risk assessment could be used to evaluate the vulnerability of some pelagic species when traditional quantitative methods for population assessment are difficult to use for pelagic predator species that require adequate protection measures (Furlong-Estrada et al., 2017).

Concerning the CCZ, it is essential to establish a permanent or semi-permanent tridimensional monitoring system for the water column, in addition to monitoring the seabed, to record key environmental variables related to the different mining activities that will take place in different layers.

However, to better understand pelagic habitat use, the "Tagging of pelagic Predators' Programme" (TOPP) has been effective. TOPP integrates biological and physical oceanographic data, in collaboration with other ocean monitoring initiatives such as GLOBEC, and the IGBP's core project, initiated by the IOC of UNESCO in 1991, to understand how global change affects the abundance, diversity, and productivity of marine populations (Hofman et al., 2002). This approach is based on synergism between scientists, industry, and governments, using animals as ocean sensors (mirroring Pacific Islanders' sensorial navigation, as previously described) (Bambridge et al., 2019; Tilot et al., 2021a, b, c).

The TOPP collects time-series data from marine migratory species supplemented by pelagic and aerial ecosystems of the eastern Pacific (Block et al., 2003). It targets key species such as air-breathing vertebrates, birds and marine mammals (pink and sooty shearwaters, laysan albatross, black footed albatross, leatherback turtles, loggerhead turtles, blue whales, fin whales and humpback whales, sperm whales), and other marine vertebrates (bluefin tuna, yellow fin tuna, white shark, salmon shark, mako shark, blue shark, *Dosidicus gigas* squid, *Mola mola*). These key species carry a variety of archival electronic tags (pressure time at depth, temperature, external environment, internal body, light level, and geolocation) that allow to record physical and chemical parameters and deduce biochemical and productivity parameters.

In this perspective, the TOPP framework, with its various tools, logistics, and oceanographic integration, is a key asset for monitoring biodiversity, critical habitats, distribution, and abundance of key species in the high seas worldwide, in particular in the CCZ. It could be used to assess the uniqueness of species assemblages, critical habitats, and the range of the movements into and out of the ecosystem (Block et al., 2003; Harrison et al., 2018). Further, standardized methods could enable comparisons between oceanic regions of the world thus facilitating the assessment and management of marine resources.

6.3.4 Indicator Species

Indicators are key tools used to assess the ecological status of the environment for ecosystem-based management (Whitfield & Elliott, 2002; Link & Browman, 2017). Monitoring a group of sentinel species (from a taxonomic and functional point of view) provides useful insights into an ecosystem or a habitat condition under the pressure of natural and anthropogenic disturbances. The monitoring of sentinel species or communities should be adapted to the pelagic domain and its different water layers including trophic processes and migrations. It would also enable cost-effective monitoring of the state of the water column throughout mining operation timeframes.

The TOPP program as described previously targets key species in the north-eastern Pacific, some of which can serve as sentinel species. Some of these species are known to dive far into the mesopelagic and sometimes abyssopelagic layers (e.g., tuna or sperm whales), hence serving as sentinel species for layers in which human monitoring is restricted.

Bioluminescent species, e.g., Myctophidae fishes, gelatinous zooplankton, crustacean, jellyfishes, cephalopods (Irigoien et al., 2014), could also serve to monitor the mesopelagic layer. Their Diel vertical migrations (DVMs) between photic and aphotic realms play a major role in benthopelagic coupling, trophically and behaviorally, by acting as carriers in the transport of carbon and nutrient to deep epibenthic communities, a key factor of the ocean biological pump. There is thus a need to integrate the efficient detection and quantification of bioluminescence, coupled to acoustic backscatter and video imagery from ultra-low-light cameras, into large-scale monitoring programs. This would enable to monitor proxies for the mass and energy transfer from the upper ocean into the deep seabed and consequently the effects of climate change (Levin et al., 2018). It could also enable to monitor the role of deep scattering DVMs in the behavioral responses and abundance and structure of deep-sea benthic communities (Chatzievangelou et al., 2021).

Further into the abyssopelagic layer, sometimes several hundreds of meters above the seabed, occur benthopelagic holothurians such as bioluminescent *Enypniastes eximia* and *Peniagone leander* (Tilot, 2006a, b; Rogacheva et al., 2012), which can serve as indicator species for near-bottom regions.

There are also Sentinels of Seabed (SOS) indicators, typical and sensitive species that enable to assess the state of benthic habitats (Serrano et al., 2022). Their use is operated in two stages with first a "typical species set" using intra-habitat similarity and frequency under reference conditions, then the "sentinel species set" generated by selecting the most sensitive species from the typical species set. This monitoring strategy using "sentinel" indicators recalls the series of monitoring program used to evaluate coral reef ecosystems such as with Reef Check (Hodgson et al., 2006).

6.3.5 Eco-hydrodynamics and Predictive Modeling

The use of mathematical and geospatial tools, such as 3D hydrodynamic models and particle dispersion models, species distribution models, combined with Geographic Information Systems (GIS), is a novel approach to understand how topography, hydrography, and species ecology influence the structure of faunal assemblages (Nihoul, 1981; Nihoul & Djenidi, 1991; Harkema & Weatherly, 1996; Moreno Navas et al., 2014). Eco-hydrodynamic modeling can also provide a better understanding of the interactions between variables such as food supply, larval transport, community composition, sediment dynamics, and pollutant dispersion, in response to hydrological factors such as currents, internal waves, upwelling, downwelling, and bottom topography (Henry et al., 2013).

Such an approach may also be used to predict the effects of anthropogenic activities. Eco-hydrodynamics have for example been applied to a cold-water coral reef ecosystem to predict the effects of bottom fishing and renewable energy installations on reef connectivity and ecosystem function (Watson & Morato, 2004; Henry et al., 2013; Moreno Navas et al., 2014; Roberts & Cairns, 2014).

The effectiveness of both sensitivity maps and alert systems will be greatly enhanced if eco-hydrodynamic models can be incorporated in them, enabling managers to visualize more directly the way in which short- or long-term changes in hydrodynamic environment will impact the biota (Moreno Navas et al., 2014; Roberts & Cairns, 2014).

7 Conclusion

Based on our analysis, we conclude that for deep-sea mining in the CCZ, it is essential to adopt a marine spatial planning and management strategy, based on an ecosystem approach, prior to decision-making with precautionary management measures, adapted preserved areas, and monitoring programs to avoid harm to marine ecosystems from the surface to the seabed. Research is highly recommended to better understand midwater ecosystems, the structure and functions of their components and respective ecosystem services in the ocean biological pump. It is also necessary to harness technological developments to better understand the impacts of deep-sea mining on faunal community dynamics, in particular local and migratory species, to assess possible resilience and adaptations over extended spatial and temporal scales to anthropogenic and natural impacts incrementally to global change.

Scientific evidence shows that for mining operations, in particular midwater discharges, to avoid epi- and mesopelagic zones because of the essential ecosystem services contained in these water layers where primary productivity is essential for all trophic foodwebs and where major fisheries operate. Consequently, discharges would have to be performed in deeper water layers and in the bathyal and abyssal domains, although faunal assemblages and life processes are poorly known at those depths. When considering vertical migrations and life cycles, would these depths be less vulnerable? Recent data have evidenced that climate change could also affect the deep seabed and that connectivity is an important factor for life cycles in the high seas and deep sea.

There is an urgent need to develop adapted management tools to monitor mining operations and identify suitable standards, thresholds, and indicators of impacts on pelagic communities. Pelagic research would need to become a key component of environmental baseline studies and monitoring efforts to ensure that the risks linked to ore collection, transport, and midwater dewatering plumes are fully evaluated. Thus, understanding the biodiversity and dynamics of midwater ecosystems and their value in terms of ecosystem services is an imperative for the scientific community, contractors, managers, and the full suite of stakeholders.

In the selection of conservation measures and area-based management strategies, predicted broad-scale and cumulative impacts to pelagic ecosystems should be considered. When considering conservation areas that would be representative of the whole water column connectivity of ecosystems from seabed to the surface, fixed preserved areas in the high seas, such as the APEIs designed by ISA in the CCZ, are not adapted. The design of moving tridimensional conservation areas with buffer zones would be more adapted to changes in space and time of interconnected ecosystems, playing key roles in the ocean biological pump. These types of large dynamic conservation areas would be essential for Apex predators and highly culturally esteemed migratory species. The best choice would be therefore to set a dynamic network of preserved areas with corridors and flexible boundaries linked to the LMPAs network in the region and the whole Pacific (as well as the network of OMPAs defined by the recently UN adopted High Seas Treaty). Also, it should be encouraged to link actions in the CCZ with other conservation and sustainable development initiatives in the region and the whole Pacific, in particular with the Pacific Island States.

The use of ecohydrodynamics modeling over bottom habitats has proven to enable better management strategies for sustainable fisheries in relatively shallow waters. If adapted to deep sea habitats, it could enable to better understand the dynamics that topography and substrate heterogeneity trigger and thus identify preferential habitats of faunal communities, as on seamounts, and thus to enable to better preserve habitats and associated faunal biodiversity.

As bioluminescence is produced by marine organisms in the whole water column as on the benthos, this phenomenon could be used as a natural indicator of good health of an ecosystem, and more specifically to identify sentinel species for each functional and trophic guild at different depths and to monitor their behavioral responses to gradual impacts in order to identify thresholds for decision-making. The TOPP program targeting key species among Apex predators and associated food web performing horizontal and vertical migrations would also be of good use to monitor naturally the water column in the CCZ using living organisms as sensors and to compare results with other regions of the Pacific as well as globally.

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