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Review

The environmental impacts of deep-sea mining

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SUMMARY

The deep sea contains a wealth of potential mineral resources, many of which are being investigated for commercial exploitation. Exploration and technical tests started in the late 1970s with an initial focus on polymetallic nodules from an abyssal region in the eastern Pacific Ocean called the Clarion-Clipperton Zone (CCZ). More recently, exploration has commenced at seafloor massive sulphides (formed by hydrothermal vents) and seamounts (for cobalt-rich crusts). Here we review the many decades of environmental research in these areas with a focus on the biodiversity baseline and the results from experimental mining or disturbance tests. Data from the CCZ have revealed that the seafloor is biodiverse, albeit at low biomass. For nodule mining, geophysical and biological impacts are persistent over at least multiple decades, although some dominant animal groups show successional recolonisation. By contrast, exploration for minerals at sulphide deposits and seamounts has been quite limited, empirical data on recovery timescales are lacking and these systems are likely to respond differently to disturbance. Deep-sea mining in any habitat could potentially generate plumes from ore dewatering which may affect pelagic ecosystems depending on the technology used. For all types of deep-sea mining, we distinguish ecological resilience and recovery from the risk of biodiversity loss (species extinction). Taxonomic data based on collections are critical to this debate; for abyssal fauna we can only currently hypothesise species ranges based on habitat availability. For vents, and to some degree seamounts, there is clear evidence that biodiversity loss from deep-sea mining is likely. If these sites were to be classified as areas of 'high biodiversity importance' under the Convention on Biological Diversity, deep-sea mining at them would not be scientifically compatible with existing policy.

Introduction

The deep sea contains a surprising range of potential mineral resources. The three most prominent are polymetallic nodules on the abyssal seabed, seafloor massive sulphide (SMS) deposits at hydrothermal vents and cobalt-rich crusts on seamounts (Figure 1). Nodules and crusts are formed by the slow precipitation of minerals out of the seawater over millions of years[1], while SMS deposits are formed by the precipitation of sulphide minerals from hot metal-rich fluids at hydrothermal vents[2]. The deep-sea areas containing these resources often lie beyond continental shelves, in depths greater than 1,000 m and out of reach of national jurisdiction. As they only started to be properly studied in the mid 20th century, deep-sea science is a young discipline, still predominantly in the exploration phase, and remains extraordinarily expensive and technically challenging. Nevertheless, interest in the commercial potential of deep-sea mining has grown rapidly in recent decades and there are now 30 areas of the deep seafloor that are contracted to an international body that regulates seabed mineral exploration in Areas Beyond National Jurisdiction: the International Seabed Authority (ISA), created by the United Nations Convention on the Law of the Sea (UNCLOS). This body has jurisdiction over a vast region of our planet, with the abyssal seafloor alone representing more than 50% of the planet's solid surface[3].

Debate on the environmental advantages or disadvantages of deep-sea mining has grown dramatically. A number of nations have called for a 'moratorium' or 'precautionary pause' on deep-sea mining[4]. The debate has moved from the academic and governmental sphere to the public — films[5], debates[6], petitions[7], celebrity endorsements in favour[8] or against[9] alongside a multitude of detailed journalistic reviews[10,11] and NGO reports[12] have placed deep-sea mining amongst the most current of environmental causes. The advocacy in these campaigns has been largely based on precautionary principles, owing to a general lack of data and the difficulty to make accurate predictions when knowledge and understanding are so scant[13]. However, over the last decade, the environmental effects of some types of deep-sea mining have been empirically assessed — in

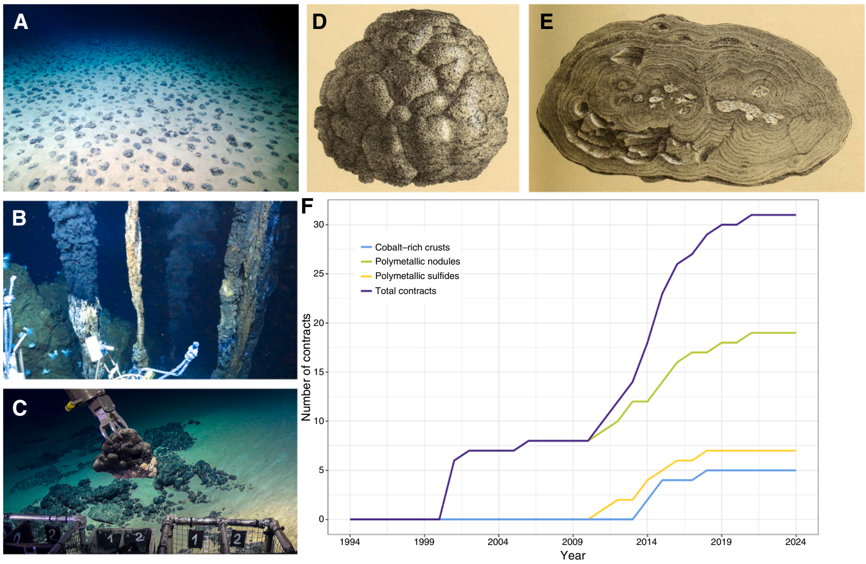

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Figure 1. The main types of deep-sea mining and recent growth in the industry.
(A) Polymetallic nodule field in the east Pacific abyss (image: NERC SMARTEX Project). (B) Hydrothermal vent (image: NERC Cayman Trough Project). (C) Cobalt-rich crust (image: NERC Tropic Seamount Project). (D,E) The first polymetallic (or manganese) nodule recovered from the Clarion-Clipperton Zone in 1875 (images © Tizard[22]). (F) Growth in exploration contracts for the three main types of deep-sea mining in international waters since the formation of the International Seabed Authority in 1994.

particular from two recent large-scale mining tests for polymetallic nodules[14–17] and the first study of the long-term impacts of a mining test carried out in the 1970s[18]. These studies are the main focus of this review.

Concurrently, in the policy sphere, a number of studies and reports have focused on providing definitions useful for policy of terms such as ‘impact’ and the definition of ‘serious harm’ (a term introduced in UNCLOS Article 165)[19–21]. These definitions are not the subject of this review, in which we focus exclusively on the current scientific understanding of baseline conditions, the measured *in situ* effects of deep-sea mining as currently known, and the projected likelihood of biodiversity loss in contrasting mining scenarios. We distinguish the effects of mining on abyssal ecosystems, hydrothermal vent sites (active or inactive) and seamounts. A potential commonality amongst the three types of mining is the release of a dewatering plume into the midwater, the possible effects of which we also consider separately.

A brief history of deep-sea mining and the environment

On the 18th February, 1873, the scientists aboard the *HMS Challenger* on the first ever global oceanographic voyage made a discovery that “*proved to be one of the most curious during the whole cruise*”[22]. South-west of the Canary Islands, they dredged from 2,700 m a dead coral and a live glass sponge attached to “*portions of manganese-iron concretions, which appeared to have been torn away from still larger masses*”[22]. Though often referred to as the discovery of nodules, the samples were likely from a seamount crust. The first true nodules were recovered much later in the voyage, south of Hawaii. On 16th September 1875, a trawl at 4,300 m “*brought up more than half a ton of manganese nodules which filled two small casks*”[22]. This was at the western end of a vast seafloor region now known as the Clarion-Clipperton Zone (CCZ) in the eastern Pacific Ocean.

Despite their extensive zoological expertise, the Challenger scientists were perhaps more interested in the nodules than the biology, rather dismissing the biodiversity of the region: “*The dredgings and trawlings in this section did not yield a very large number of deep-sea animals*”[22]. This founded the notion that deep-sea life was generally low in abundance and diversity. The American zoologist Alexander Agassiz in 1899 sampled right in the middle of the CCZ, recovering numerous nodules and arrived at similar conclusions to the Challenger team, “*that at great depths, at considerable distances from land and away from great oceanic current, there is comparatively little animal life*”[23]. The myth of the low-diversity, desert-like deep sea continued through the first part of the 20th century. The concept of mining the depths was based on John Mero’s 1965 book *The Mineral Resources of the Sea*[24]. Building on advances in deep-sea photography, it showed the vast commercial potential of deep-sea nodule mining and led directly to the first ‘nodule-rush’ in the central Pacific from the late 1960s through to 1980, which culminated in several tests of mining operations that were almost brought to commercial viability (Figure 2).

During the same period, two paradigm-shifting biological discoveries were made in the deep Pacific: in 1977, high-biomass biological communities were discovered around active hydrothermal vents in the eastern Pacific[25]; and — less famous — research from Woods Hole Oceanographic Institution found that deep-sea sediments could hold high levels of biodiversity, albeit for small bodied species at low abundances[26]. This latter discovery in particular was revolutionary as it implied that biodiversity in the deep-sea, given its vast area, was extremely high globally.

By the late 1970s, there were at least three active exploration consortia working in the CCZ developing nodule-recovery systems[27]. Environmental concerns were in general considered negligible[28], although interest was raised in the press as early as 1977[29]. Nevertheless, the newly formed US National Oceanic and Atmospheric Administration (NOAA) commissioned an environmental survey of the entire CCZ region using quantitative methods. This was the Deep Ocean Mining Environmental Survey (DOMES) that set the first standard for any environmental work related to deep-sea mining[30,31]. The result of the NOAA studies was that, although abundance was extremely low, species diversity of the larger animals was high relative to other known deep-sea sites. The observation that “*Faunal diversity is extremely high, with deposit feeders comprising the overwhelming majority. Most species are rare, being encountered only once*”[32] summed up all of what was known about abyssal

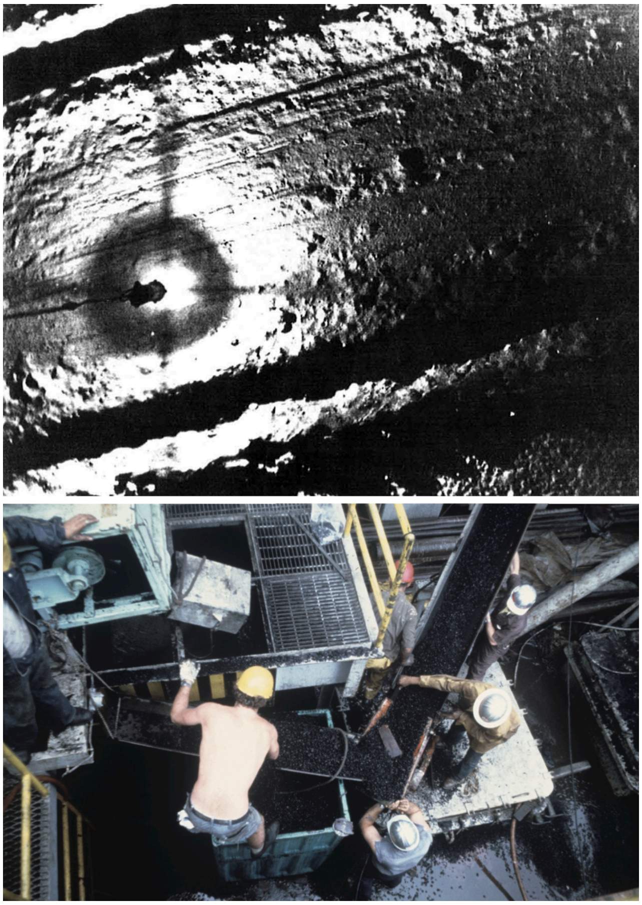

Figure 2. Early attempts at deep-sea mining.
(Top) An early image (1983) of a deep-sea mining test track made in 1978 by the Ocean Mining Associates 550-tonne nodule collection using an MV-1 collector (image: [208]). (Bottom) 900 tonnes of nodules being collected by the Ocean Mining Inc. consortium in 1978 (image: Ted Brockett).

biodiversity in 1974 and perhaps much of what is known today. This summary supported the idea of the abyss as a stable, food-poor but biodiverse ecosystem in opposition to general ecological theory that would suggest low diversity in such situations[33].

Despite the conceptual and technological leap in deep-sea biology, the general view that the ecological impacts of mining in the deep sea would be intrinsically low persisted through the end of the 20th century. A 1987 NOAA report to the US Senate on the DOMES study concluded that "*most of the original environmental concerns have a very low probability of causing a significant adverse environmental impact*"[34]. Part of this view may have been influenced by classic seabed photographs that show little obvious marine life (Figure 3A). It persisted for two reasons: scale-dependency, by which the vast spatial extent and low abundance conceal potential biodiversity; and the lack of sampling of the smaller size-fraction of the sediment requiring high-quality taxonomic and zoological research[35].

Through the end of the 20th century, experimental studies in the CCZ and comparable abyssal regions, such as the East Peru Basin, focused on the impacts of sediment plumes that could be generated by the movement of a mining machine and small-scale disturbances designed to mimic a mining test[27,36].

Commercial interest grew following the signing of a contract between the ISA and Germany in 2006. By 2021, there were 11 new exploration contracts in the CCZ, fuelled by the growing demand for battery minerals — especially cobalt and nickel that are abundant in nodules[37]. This period saw a similar growth of interest in the mining of vents, or more accurately the SMS deposits that they form, which are rich in copper, zinc and lead[38]. The first contract for SMS exploration in international waters was signed in 2011, and there are now a total of seven contracts in the mid-Atlantic ridge and Indian Ocean. The first contracts for the mineral exploration of cobalt-rich crusts at seamounts were signed in 2014, and there are now three such contracts in the Western Pacific[39].

UNCLOS was not primarily intended as an environmental treaty, but embedded within the 'Part XI' that covered the creation of the ISA, and the regulation of seabed mining was a commitment to the protection of the environment, to which several articles of the treaty refer. A critical development in environmental regulation for deep-sea mining took place in 2012 with the implementation of a network of 'Areas of Particular Environmental Interest' (APEIs)[40]. These protected zones were designed based on precautionary principles but also had to operate around the pre-existing contract holders, which in 2007 was only the new German contract and the so-called 'Pioneer' contractors that had pre-UNCLOS claims (Figure 4).

Notably, this regulatory process involved the creation of a spatial management plan that included protected regions relatively early in the exploration phase, before many exploration contracts, and was later modified and expanded as more scientific knowledge was gained[41,42]. The current CCZ APEI network consists of 13 regions amounting to approximately 1.97 million km^2 of protected seabed, approximately 30% of the total area of the CCZ.

Alongside the international framework developed under UNCLOS, there has been increasing exploration of nation states' waters for potential deep-sea minerals. An early example was the work of Nautilus Minerals at the Solwara I deposit in the Exclusive Economic Zone (EEZ) of Papua New Guinea[43]. A substantial environmental survey was carried out at this site[44] alongside mineral resource exploration, but the company went bankrupt, and the project halted. More recently, Japan has undertaken test mining of SMS in the Okinawa Trough with some environmental data appearing in the scientific literature[45], and the recent discovery of >200 Mt of manganese nodules within Japan's EEZ has accelerated plans for the experimental extraction of these minerals[46]. In the EEZ of the Cook Islands (a region of 2 million km^2) that lies far to the west of the CCZ, three contracts have been signed with the Cook Islands Government to undertake environmental and resource exploration[47]. In Norway, plans to open up 280,000 km^2 of its deep seabed to mineral exploration and exploitation have, for now, been suspended among environmental concerns and legal challenges. From an environmental standpoint, countries that are signatories to UNCLOS are required to meet the same standards for deep-sea mining in their own waters as those carried out in international waters[48].

In summary, the emergence of deep-sea mining as a potential new industry has occurred in parallel with a rapid growth in understanding of deep-sea biology, in particular the remarkable

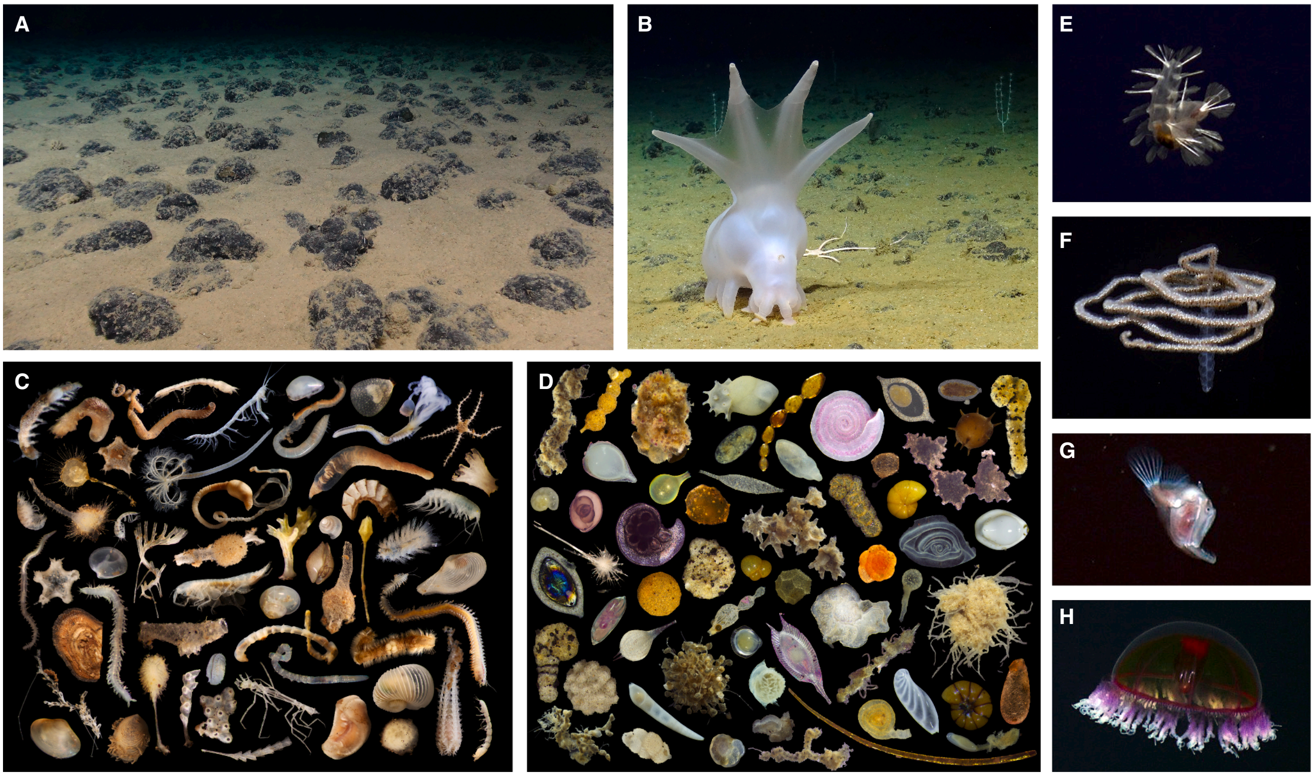

Figure 3. Biodiversity in polymetallic nodule provinces.
(A) A general oblique view of the abyssal seabed in the Clarion-Clipperton Zone, showing almost no visible fauna. (B) *Amperima* sp., a megafaunal sea cucumber on the seafloor in the eastern CCZ. (C) Live abyssal macrofaunal species extracted from sediment and nodules and imaged under a photomicroscope. (D) Live abyssal foraminiferal species imaged under a microscope. (E–H) Biodiversity in the water column of the eastern CCZ. (E) *Flota* sp., a pelagic polychaete common in the abyssopelagic. (F) *Apolemia lanosa*, a large siphonophore. (G) The anglerfish *Melanocetus* sp. (H) *Crossota milsae*. Images: (A,B) National Oceanography Centre and Natural History Museum, NERC SMARTEX project; (C) Natural History Museum; (D) Bryan O'Malley, Eckerd College; (E–H) Drazen and Lindsay, NORI-D baseline project.

biodiversity of deep-sea sediments and the novelty of fauna at active hydrothermal systems. Deep-sea mining, while growing rapidly in terms of exploration, is perhaps an unusual industry in that both national and international regulatory controls, such as the creation of protected areas, have been implemented before the start of any commercial-scale activity.

Effects of deep-sea mining on abyssal seafloor ecosystems

The abyssal seafloor, including plains and sedimented hills, is the largest contiguous habitat on the planet[49], but has also been divided into many ecoregions or provinces[50]. With some exceptions, it is characterised by sedimented abyssal plains with relatively low relief, low temperatures (0.5–3°C), slow currents, as well as low food availability and biomass. The main target for abyssal seabed mining, the 6 million km^2 CCZ, has been studied since the 1960s, with the first quantitative baseline biological survey in the 1970s[30] and the first Environmental Impact Statement created in 1981[31]. The CCZ is characterised by flat terrain and a relatively high abundance of polymetallic nodules (10–15 kg/m^2) which form a potential ore for metals such as cobalt, copper and nickel[37].

From a purely geophysical standpoint, the possible effects of mining nodules on an abyssal plain are now quite well understood. Nodule-collecting machines, potentially up to 15 m wide, would drive over the seabed, removing the nodules and the surface layer of the sediment, creating tracks of compacted, nodule-free sediment (Figure 5). Behind the vehicle, re-suspended sediment would form a benthic plume that settles over the tracks and nearby areas. A two-day test of a 4 m-wide nodule collector has shown that the benthic plume is constrained to the seabed by turbidity flow, and that the thickness of sediment deposition behind the vehicle follows a power-law relationship with distance[51]. Within 100 m of the mining track, the layer of sedimentation was ~3 cm, and sediment deposition was evident to 1,500 m but not detectable visually beyond 1,800 m.

A typical commercial-scale abyssal nodule mine is expected, for economic reasons, to aim to extract approximately three million tonnes (Mt) per year[52]. Thus a 20-year CCZ nodule mine, at typical nodule densities, would need to occupy an area of about 8,500 km^2, roughly the size of the island of Crete[52]. The actual area of geophysical impact would be expected to be larger than this owing to sediment plumes, but it would depend on the mining pattern used and mitigation measures designed to reduce the plume footprint. For example, if the mining tracks were spaced further apart, the total impacted area would be much greater and be a combination of both tracks and sedimented seafloor. If the tracks were not spaced, most of the

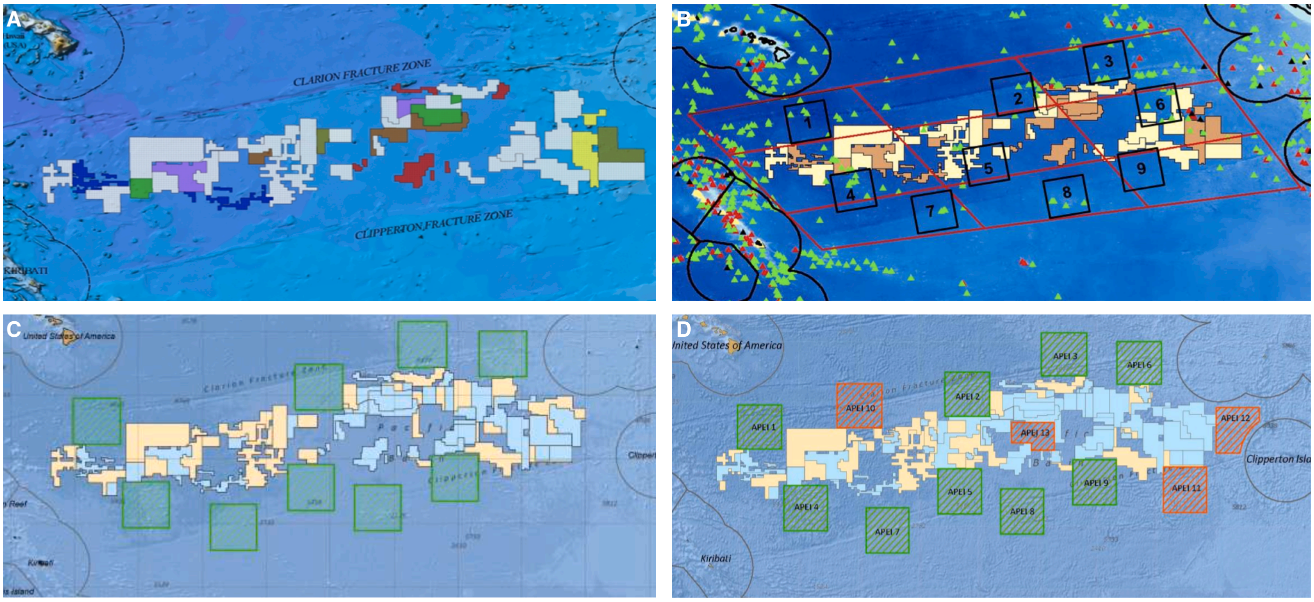

Figure 4. The 18-year evolution of a regional management plan in the Clarion-Clipperton Zone (CCZ) deep-sea mining area.
(A) The CCZ contract exploration regions in 2008 prior to the regional plan. (B) Proposed 'preservation reference areas' suggested by the Kaplan Project and in an ISA Technical Study[209]. (C) Final decision by the ISA Council created the first Areas of Particular Environmental Interest (APEI) network in 2012[210]. (D) Refinement of the APEI network in 2021 to include three new APEIs based on the joint ISA and DeepCCZ project workshop held in October 2019 in Friday Harbor[211] (map images © ISA news, reused with permission).

plume-impacted regions would also be mined, and hence the total areal impact of the mine, at the seafloor at least, would not expand much beyond the tracks. This latter scenario is unlikely, as in many areas nodules are not uniformly distributed and often occur in strips several kilometres wide[53,54].

To understand the potential effects of abyssal nodule mining on deep-sea life it is thus necessary to measure the effects of mining on the seafloor biota in both areas directly driven over by the test vehicles and adjacent areas covered by sediment. These measurements also need to be undertaken in the context of the baseline conditions including natural temporal variability. In general, the fauna of the CCZ has been classified by size into megafauna (animals greater than ∼1 cm and visible in photographs), macrofauna (greater than 0.3 mm) and meiofauna (greater than 0.032 mm). Protists (*e.g.* foraminifera) and microbial life have in general been studied separately.

Baseline ecological patterns in the CCZ

In the nodule-containing provinces of the CCZ, the baseline abundance and community composition of megafauna are reasonably well studied, at least compared to other deep-sea regions. Studies as far back as the 1970s included innovative broad spatial assessments in several areas[30,55] and relatively long-term observations[56]. Typically, much larger areas can be assessed by imaging than with sediment coring, although with imaging animals are identified typically only at higher taxonomic levels. As megafauna is sparse in the CCZ, with only 0.1–1 individual per m^2, broad areas need to be covered with seafloor photography to encounter enough animals. Imaging studies have now become critical for understanding patterns in abyssal faunal communities[57,58]. One key finding from such studies is that the community composition of megafauna shifts across the CCZ: the eastern region is dominated by brittle stars and soft corals, while the western region is dominated by anemones and sea cucumbers[58]. Much of the biodiversity depends on the nodules for habitat, and with increasing nodule density or type, animal abundance increases and community composition varies[57,59–62]. Although studies are not typically at species-level, putative species (morphotypes) can be counted and are used to form a lower diversity estimate. A recent compilation of much of the existing photographic information, including over 50,000 specimen images, has identified 411 megafaunal morphotypes present in the CCZ[63], a number that is continually increasing with new investigation.

For macrofauna, there is an extensive dataset of benthic density and composition from a long history of taking replicated core samples that provide very good density and compositional data, albeit often at coarse taxonomic levels[30,64–70]. The macrofauna in the CCZ can be split into two categories: those that live in the sediment (*e.g.* polychaetes, crustaceans) and those that live attached to the nodules (*e.g.* sponges, bryozoans). The majority of published work to date has focused on the sediment-dwelling fauna, with very few studies considering the nodule-fauna[71,72], whose biodiversity, biogeography and ecology thus remain largely unknown. The density of sediment macrofauna is roughly 100–1,000 individuals per m^2, about 40% of which are polychaete worms, 30% are isopod, amphipod or tanaid crustaceans, about 10% molluscs and the remaining 20% are other groups, such as echinoderms, cnidarians or minor phyla (Figure 3). There is significant spatial variation in the patterns of macrofaunal density across the CCZ, with a general pattern of increasing density towards the eastern end of the CCZ, which also has higher productivity in surface waters. Decadal-scale temporal drivers, such as the El Niño Southern Oscillation, are likely to also play a role in driving macrofaunal biodiversity patterns[17,69]. Measuring this

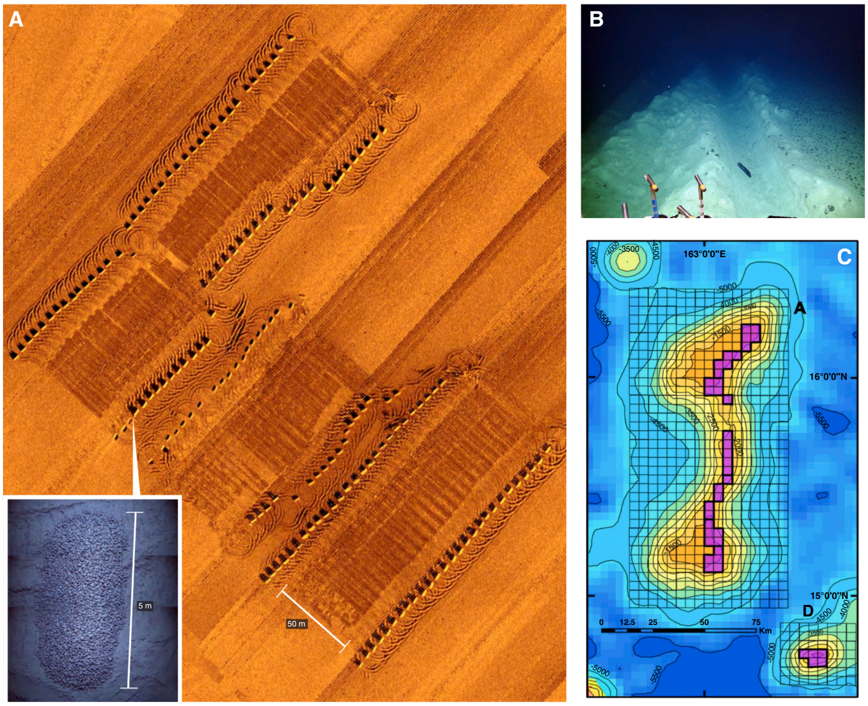

Figure 5. Actual and potential direct geophysical impacts of deep-sea mining.
(A) Autonomous Underwater Vehicle sidescan sonar image of a completed nodule mining test in the eastern Pacific abyssal plain conducted in April 2019. The image shows the 50 m-long mining tracks in a 'mowing the lawn' pattern, and (inset) the nodules piled at the end of each track — the test did not include a nodule recovery system (image used with permission of Global Sea Mineral Resources). (B) The 8 m-wide mining track created by the Ocean Minerals Company (OMCO) mining machine in 1979 in the eastern Pacific Clarion-Clipperton Zone. Image taken in 2023 after 44 years (image: National Oceanography Centre and Natural History Museum, SMARTEX Project). (C) Hypothetical extent of a commercial-scale cobalt crust mine on a guyot (flat-topped seamount) in the west Pacific. Seven 100 km^2 blocks have been selected for exploration, each consisting of five 20 km^2 (4 x 5 km) sub-blocks. Approximately 13 of these sub-blocks would be required to create a commercial 20-year mine (image reused from[150], with permission by Taylor & Francis Ltd).

variability is critical to detecting disturbance impacts, but it is also important to note that benthic macrofaunal density is very low in the CCZ. As an example, deep sea sediments in the Southern Ocean harbour 16,000–21,000 macrofaunal individuals per m^2, more than three orders of magnitude more than in the CCZ[73]. The low density of animals in the CCZ, and generally in the tropical abyss under the oceanic gyres, is caused by extremely low food input to the seafloor owing to oligotrophic surface waters[32].

Relative to its abundance, macrofaunal biodiversity of the CCZ is high. Typically, studies record many singleton species that increase species diversity[64,65,67,70]. Although the deep sea is often described as being high in diversity, few studies actually compare it quantitatively with other habitats[74]. One study has compared diversity in the CCZ with equivalent deep-sea regions, recording polychaete diversity to be 40–50% higher in the CCZ, but with some methodological caveats[64]. Critical to assessing the potential for biodiversity loss in the speciose CCZ macrofauna is an understanding of its biogeographic ranges and population connectivity. Two threads have emerged in recent synthesis studies: first, more abundant taxa have been shown to have very broad ranges (>5,000 km) with often high degrees of connectivity at ocean-basin scale[64,75,76]; second, for rare species that account for most of the diversity, under-sampling at local sites means that it is impossible to know whether they are true endemics or have simply been missed when sampling. This paradox presents huge challenges in predicting biodiversity loss from deep-sea mining in the CCZ.

For meiofauna, there is only limited information for any deep-sea site, and less so for the CCZ. The abyssal metazoan meiobenthos includes many taxa, usually dominated by nematodes (70 to >90%) and harpacticoid copepods (1–15%). These relative abundances are remarkably consistent throughout the abyssal plains. Other groups that are frequently found are turbellarians, ostracods, kinorhynchs, tardigrades, gastrotrichs, halacarid mites, loriciferans and meiobenthic polychaetes. However, these groups often comprise only <1% of total meiofauna. In the abyssal plains and in the CCZ, meiobenthic density varies on the order 10,000s to 100,000s of individuals per m^2 [77–79], about two orders of magnitude higher than the macrofauna, but one or two orders of magnitude lower than meiofaunal densities in coastal waters. Variability in meiobenthic abundance is often related to substantial patchiness on the deep-sea floor, largely driven by the availability of food resources derived from the episodic influx of decaying plant matter from the surface, as well as the presence of nodules as habitat[80].

While animals are integral to abyssal sedimentary communities, it is equally important to consider protozoans, in particular benthic foraminifera. Abyssal benthic habitats comprise soft sediment and hard substrates, such as nodules and biogenic structures; foraminifera are the most abundant eukaryotes across mega-, macro-, and meiofaunal size classes in each habitat type (Figure 3D)[71,72,81–86]. Foraminiferans play key roles in ecosystem functioning, including biogeochemical cycling and habitat provisioning[87–89]. Their dominance reflects biological advantages such as reproductive plasticity (both asexual and sexual), diverse construction of tests (i.e. shells built from agglutinated sediment particles, secreted organic material or secreted calcium carbonate) and varied trophic strategies, including deposit feeding, bacterivory, carnivory and osmotrophy[87,90]. These adaptations enable their persistence in oligotrophic conditions and their resilience to environmental disturbance[18,91].

Recent quantitative studies have documented nearly 800 foraminiferan morphospecies with standing stocks exceeding 100,000 living individuals per m^2, dominated by the class Monothalamea[92,93]. Among the foraminifera, Xenophyophores are the single-celled giants of abyssal plains, reaching up to 20 cm in diameter, that dominate megafauna-sized communities[53]. Their agglutinated tests are a source of biogenic habitat hosting associated organisms including animals, microbes and protists. Xenophyophores are recognised as indicators for Vulnerable Marine Ecosystems under international conservation frameworks[94–96] and surveys in the eastern CCZ have identified 36 morphospecies, including 34 new to science[97]. The ISA has accordingly recognised foraminifera as key indicators in environmental impact assessments for areas targeted for seabed mining[98,99].

Prokaryotic life in the CCZ has been studied only very recently. Initial investigations focused on the nodules themselves with a view to understanding the role of microbes in nodule growth[100]. More recently, a series of investigations in the eastern CCZ has described the distinct prokaryotic communities in the nodules, the sediment and the overlying water column[101,102]. These studies have shown that the microbial community in bottom waters is distinct from the sediments and nodules, though the latter do share a number of taxa. Across the CCZ there is some emerging evidence of regional shifts in species composition[102]. A focus of microbial studies is their dominant role in ecosystem function such as organic carbon sequestration[103].

In summary, our knowledge of the baseline ecology of the abyssal CCZ is generally limited to overviews of faunal abundance, composition and diversity. These variables have been more intensively studied in the larger animals, and we have limited knowledge of the ecological processes that underpin temporal changes in communities, and the recovery timescales following disturbance. The main insights into these come from the various tests of deep-sea mining systems that have taken place over the last 50 years.

Impacts of deep-sea mining tests on abyssal ecology

There have been 12 experiments of nodule mining disturbance using vehicles or simulated disturbance (Table 1 and Figure 6). Of these, just three include a replicated 'before-after-control-impact' design[104]. Most of the studies rely on spatial analogues or only a single control site. Measured effects fall into two main categories: the impacts in the direct path of the collector and the impacts of sediment deposited onto areas adjacent to the mined region.

The direct, long-term impact of a large-scale nodule collector vehicle has only been comprehensively studied once[18]. In 1979, a large 9 m-wide nodule collector was trialled by the US Ocean Minerals Company (OMCO) in the central CCZ[105]. Although its design differed from modern technology, the test does provide insight into the decadal-scale effects of mining disturbance. In 2023, tracks were still clearly recognisable, indicating a persistent geophysical impact[18] (Figure 5). There was no discernible spatial impact on the density of macrofauna and foraminifera when compared with nearby unimpacted sites. However, megafauna density was reduced in the areas from which nodules had been collected, compared to pre-impact and control sites, and a novel megafaunal assemblage had formed in the vehicle's propulsion tracks with higher dominance of certain species. There was clear evidence of recolonisation by a species of xenophyophore in the most disturbed parts of the track, with higher densities than in undisturbed regions. This pattern is similar to what is observed in natural disturbances, such as volcanic ash falls[106]. While the physical impacts of the sediment plume could still be detected, there was no clear impact of the plume on benthic biology.

Two other large-scale nodule collectors have also recently been tested, the Patania test in 2021 and the Nauru Ocean Resources Inc. test in 2022 (operated by The Metals Company). For the former, only the geophysical aspects of the plume[51,107] and impacts on meiofauna have so far been assessed. Meiofauna showed no clear impact, but replication of samples was very limited[14]. For the Nauru test, a comprehensive study of the impacts on sediment macrofauna showed a reduction of 37% in density and 32% in diversity in combination with increased community variability directly within the mining tracks. Although the plume-impacted sites showed no obvious change in abundance, a shift in community composition could be observed[17].

The DISCOL experiment[36] is perhaps the most comprehensive study of disturbance in an abyssal system, although it took place in the East Peru Basin (not the CCZ) and was based on seafloor ploughing rather than nodule collection. The site was monitored before and after disturbance at various time points. There was a mixed pattern of ecological recovery: microbial activity remained depressed for >26 years[108], whereas sediment meiofauna (nematode) and macrofauna communities, although still faunistically changed, were not noticeably impacted in abundance more than seven years after disturbance, implying a degree of recovery[109,110]. For megafauna, there was some recovery after seven years but after 26 years, impacts were still detectable including in regions impacted by the sediment plume[111,112].

The remaining impact studies come from smaller-scale disturbance experiments. In the French contract area in the central CCZ, a submersible cruise in 2004 investigated what was termed an 'OMCO dredge track'[113] and, erroneously, the OMCO 'mining track'[114]. The site investigated was 420 km to the west of the known OMCO 1979 collector test[18], and it is highly likely they investigated another dredge track made during one of 16 expeditions carried out between 1978–81[55]. An impact on meiofauna was reported 26 years after the disturbance based on spatial comparison[114], although this is inconsistent with other meiofaunal data[115]. Oxygen consumption and respiration were assessed in the track and a control site, reporting no significant differences apart from the general geochemistry of the sediment[113]. The remaining abyssal impact studies (OMA, RUM-3, BIE-II, JET, IOMBIE, INDEX) either could not detect impact or suffered from issues with experimental control and replication (Table 1).

In summary, mining tests in the CCZ yield a mixed picture owing to different collection and disturbance technologies and different spatial or temporal follow-up monitoring. Nonetheless, at least a multi-decadal scale impact on some faunal components is evident while others have recovered to varying degrees. For some faunal groups, there is evidence of recolonisation and community succession. Most studies have not been able to measure the impacts of sediment plumes either because the impact was limited[18] or due to methodological challenges. However, there is evidence of long-term impacts of sedimentation in the DISCOL site[112]. Significant natural variance in benthic components, such as macrofaunal abundance[17,69], suggests that the baseline degree of natural temporal variation may be higher than previously thought. In addition, it is possible that the use of newer technologies in recent nodule collection tests rather than ploughing or sediment-churning methods used in the earlier

Table 1. Summary of mining disturbance experiments in polymetallic nodule regions (including the CCZ, Indian Ocean and Peru Basin DISCOL site) with notes on impacts recorded in the fauna.

Test vehicle / project	Time of impact	Time of post-impact studies	Meio/macrofaunal impact	Megafaunal impact	Notes	References
OMI	March–May 1978	May 1978	Not detected (low replication)	Not measured	900 t of nodules recovered. Majority of impact work was on surface discharge plume; limited benthic samples	212
OMA (MV)	November 1978	June 1983	Not detected	Not measured	Samples ‘near’ track only	208
OMCO	March 1979	February 2023	No impact (or potentially recovery) on faunal abundance after 44 years in track or plume	After 44 yrs persistent reduced density and diversity in collection area, higher dominance in propulsion track	No samples taken immediately post-impact, no samples pre-impact for macrofauna	18,27
‘OMCO’ Khripounoff	Unknown	July 2004	Published evidence of some meiofaunal impact, but contrasting results	Residual impact on megafaunal density	Persistent geochemical changes noted, but respiration rate in/out track no different. Track not made by OMCO mining machine	60,113,114
RUM-3 ‘QUAGMIRE’	May 1990	May 1990	Not measured	Not measured	Experiment failure	213
BIE-II	August 1993	September 1993	Not detected overall	Not measured	Some individual polychaete taxa ‘responded’	214
JET	1991	1994	Not detected	Possibly lower densities in plume area	Statistically not significant	215
IOMBIE	July 1995	1995, April 1997, June 2000	Meiofauna initial decline and later recovery but non-significant, macrofauna effects not detected. Foraminifera (>250 μm) effects not detected	Indirectly measured	Only a few photos of the tracks. Meiofauna sets of multicores at different post-disturbance times, Disturber caused heterogeneity at seafloor	216–218
INDEX	1997	1997	Decreased macrofauna density	Not measured	Low sample size	219
DISCOL	March 1989	September 1989, February 1992, February 1996, August 2015	Macrofauna impacted, then abundance recovered >7 yrs, residual community impact >7 yrs	Impact detected, some recovery >7 yrs, impacts still detectable >26 yrs	Recovery varied between taxa	36,107–109
GSR Patania II	April 2021	April 2021	No significant impact detected on meiofauna	Not yet published	Clear data on constraint of plume. Limited replication (n = 3)	11,51
NORI-D Allseas/TMC	October 2022	December 2022	Macrofaunal density reduced by 37% in track sites, no impact of plume on density. Diversity reduced in both track and plume	Not yet published	Scientific papers in preparation	17,107

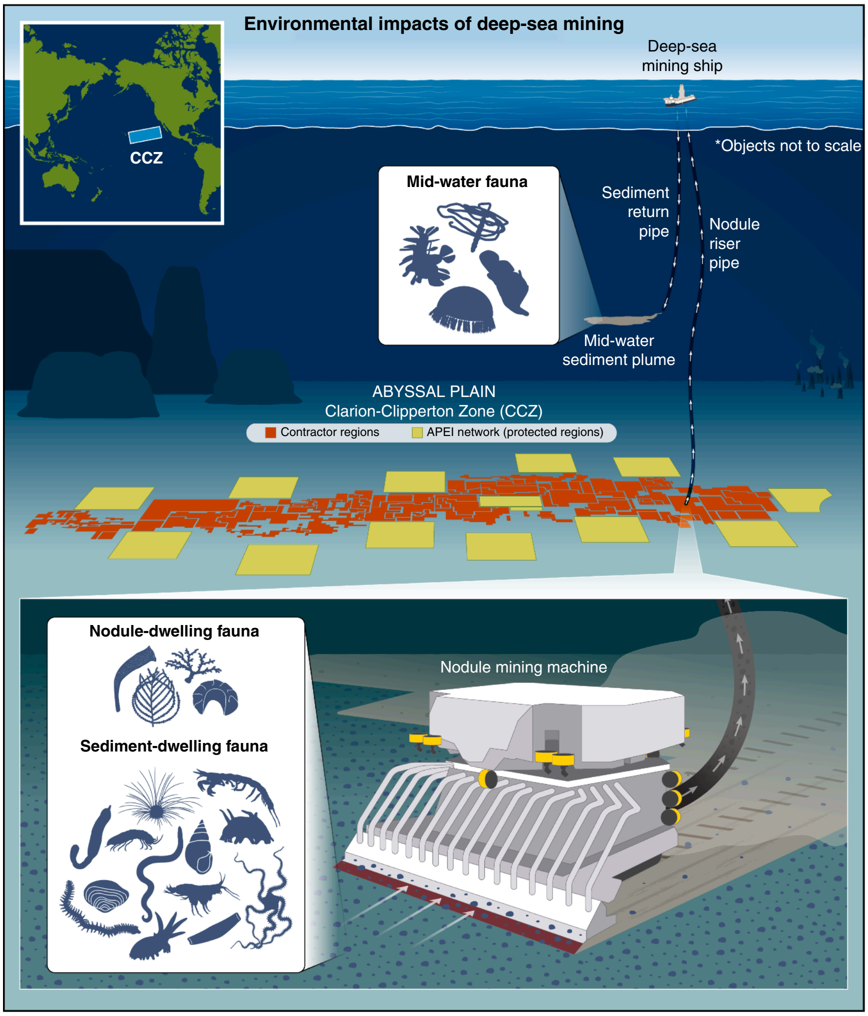

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Figure 6. The impacts of deep-sea mining.
Summary schematic of the main environmental impacts of deep-sea polymetallic nodule mining, in the context of the broader regional abyssal region and areas set aside for marine protection under current regulatory guidelines (image: Julie Sung, CellPress, and Eva Stewart, Natural History Museum).

experiments will limit the spatio-temporal impact of the benthic plume now thought to be more constrained than previously thought[51,116]. It is important to note that tests carried out to date have been conducted at smaller spatial and temporal scales than full-scale mining would be, limiting to some degree our ability to generalize results[27].

Effects of deep-sea mining on hydrothermal vents

Deep-sea hydrothermal vents were first discovered in the eastern Pacific in 1977 — one of the most remarkable biological discoveries of the 20th century[2]. Since then vents have been found globally at mid-ocean ridges, back-arc basins and volcanic arcs. The active ‘vent chimneys’ from which mineral-rich hydrothermal fluids erupt into the ocean are typically part of a much-larger seafloor massive sulphide (SMS) deposit that is the primary target of mining interest, with copper, zinc and lead being the main metals of interest and secondarily gold and silver.

In contrast to nodule mining, the basic geophysical footprint of a potential deep-water SMS mine is not well understood, nor is it clear how it might be mined. The methods of mining inactive or active vent sites remain essentially unknown, other than the obvious adaptation of vehicles used on terrestrial SMS deposits[117,118]. The essential premise of SMS mining is that the substrate including active or inactive vent chimneys would be removed by the mining machines, significantly altering the geomorphology of the seabed[119]. There is no clear published guidance from the mining community regarding the scale on which this would occur; the only precedents are the work at Solwara I — an SMS mound about 2 km in diameter and rising 200 m above the seafloor[120] — and in the Okinawa Trough, the location of the only known SMS mining test[45]. In the latter case, only 26 m^2 of the seafloor was excavated over six hours.

Active hydrothermal vents are colonised by a complex community of animals that are highly adapted to the vent environment, including tolerance to heat and chemical extremes. Vent animals often host chemosynthetic bacteria in symbioses that provide nutrition from hydrothermal fluid[121]. Many of the resident species are highly endemic, and only a few vent species have been found in other deep-sea habitats, such as cold seeps, whale-falls, wood-falls and other reducing ennvironments[122,123], although vent species typically share an evolutionary history with species from such habitats[124,125].

In contrast to the continuous abyssal plain habitat, active hydrothermal vents occur as island-like ‘vent fields’: clusters of vent chimneys occurring together. The average area of habitat within a vent field may be as small as ∼30 m in diameter[126]. Individual vent fields are separated by distances from tens to hundreds of kilometres depending on the volcanic and tectonic activity of a region[127], creating a fragmented habitat for metapopulations of vent fauna. In comparison with the 6 million km^2 area of the CCZ, the global area of active hydrothermal vent habitat is estimated to be less than 50 km^2 in total[126]. In further contrast to the abyssal plain, hydrothermal vents harbour high animal biomass but with low diversity, at least at the scale of individual vent fields. Fewer than 100 species have been typically recorded per vent field at more-thoroughly sampled sites, even when meiofaunal taxa have been included[128]. At larger scales, there is regional variation in the taxonomic composition of fauna colonising vent fields, and the biogeographic provinces proposed for vent taxa[129–132] largely conform with those established for other deep-sea fauna[50]. However, further sampling is required within each biogeographic province before any confident estimate of global species richness at vents can be attempted[133].

In addition to being insular habitats, some vent fields are ephemeral in their activity. Volcanic and tectonic activity can disrupt the flow of hydrothermal fluid at entire vent fields, and the frequency of such disturbance varies with geological setting. On fast-spreading mid-ocean ridges, such as the East Pacific Rise, activity at an individual vent field may last for decades[134,135]. But on slow-spreading ridges, such as the Mid-Atlantic Ridge, which constitute 50% of the global mid-ocean ridge system, geochronology of sulphide deposits indicates that hydrothermal activity may persist for millennia at individual vent fields[136]. Activity is also sporadic, with individual vent fields switching on and off for thousands of years. The overall persistence of hydrothermal activity at vent fields on slow-spreading ridges creates larger SMS deposits, which are of greater interest for mining[137].

Studies on the ecological succession from ‘time zero’ (the onset of activity or if a vent has been defaunated by an eruption) at vent fields on fast-spreading ridges have identified pioneer and late-stage species in their succession[135]. However, so far no one has observed succession at a vent field on a slow-spreading ridge, which is the target of interest for SMS mining. Decadal-scale time-series studies of fauna at vent fields on the Mid-Atlantic Ridge, which have been conducted the longest on slow-spreading ridges, show stability in faunal composition at vent-field scale, consistent with a climax state of succession[128,138]. Within a vent field, individual vent chimneys typically follow a pattern of geomorphological development, as a consequence of mineralisation and its effects on hydrothermal flow through the structure[139]. Vent chimneys often initially grow as relatively thin structures with vigorous high-temperature (“black-smoker”) venting from an orifice at their top; then they may develop lateral platforms and flanges that emit more extensive diffuse flow of cooler hydrothermal fluids; and finally, they become inactive (‘extinct’) sulphide structures as hydrothermal flow ceases.

Mining an active vent field would reset its succession to time zero, removing vent chimneys but not necessarily disrupting the underlying flow of fluids. Chimneys will regrow and be colonised by larvae from the regional pool of vent fauna, just as they would when venting begins or resumes naturally. However, all the chimneys in the vent field will initially develop the ‘young’ morphology — there will be no mature chimney habitat in vent fields immediately after mining. If mining operations reset succession at vent fields across a region at a higher rate than they would reset naturally, there could be an overall loss of mature vent chimney metapopulations for that region and a risk of extinction for any species that only occur in later successional stages.

It is possible to deduce likely successional sequences of vent fauna on slow-spreading ridges by comparing the taxa that colonise chimneys at different stages of geomorphogical development within a vent field[140]. For example, at the Longqi Vent Field on the ultraslow-spreading Southwest Indian Ridge, which is in an ISA exploration licence area for SMS mining, black-smoker chimneys with ‘young’ morphology are dominated by taxa including alvinocaridid shrimps[132]. On mature chimneys with diffuse flow from lateral platforms and flanges, the fauna is dominated by peltospirid gastropods, eolepadid barnacles and bathymodiolin mussels, while ‘extinct’ chimneys with little visible hydrothermal flow are occupied by taxa including raphitomid gastropods[132]. Removing mature and extinct chimneys by mining would therefore remove habitat for several groups, even if new chimneys start to regrow immediately afterwards.

In terms of experimental impact analyses, vent mining has been much less well studied than nodule mining. A single experimental study, which followed the impacts of SMS test mining in the Okinawa trough from 2017[45], found impacts on the communities in sediment cores close to the mining site, some of which (microbes and meiofauna) recovered after three years. This single study is clearly inadequate to base environmental impact assessments on, in part because it was limited to the small fauna living within sediments, rather than the charismatic animals living on the vent chimneys themselves — a clear concern for conservation.

Inactive sulphides — ‘extinct’ vent fields where hydrothermal activity has ceased but the mineral deposits it created remain — are more likely to be a prospect for mining than active vent fields[141]. Inactive sulphides form a hard substratum that can be colonised by typical benthic suspension feeders such as corals, bryozoans and sponges[142,143], but our knowledge of their specific ecology on these substrates is lacking[144]. Inactive SMS deposits are also quite likely to be covered by sediment, further complicating the picture with regards to potential mining impacts. One inactive SMS mound 30 km from a nearby active vent was investigated on the Mohns Ridge in the Arctic, revealing fauna typical of Arctic bathyal systems[145]. Inactive vent fields may still contain low levels of hydrothermal flow, and surveys of inactive vent fields in the Indian Ocean have recorded vent species known from nearby active sites[142]. A recent study has found a macrofaunal assemblage dominated by gastropods on an inactive sulphide deposit on the East Pacific Rise, which may be unique to this habitat and supported by rock-based microbial chemosynthesis[146]. Additionally, some megafaunal species, though wide-ranging, may be endemic to inactive sulphide habitats[147]. Any regulatory protection of active vents would therefore require clear definitions to distinguish active and inactive sites[144]. If further research finds that inactive sulphides host unique fauna, then mining of their SMS deposits could pose a threat of biodiversity loss like that at active hydrothermal vents.

In summary, with their island-like distribution and high degrees of endemism and functional novelty, active hydrothermal vents are almost the complete opposite to abyssal ecosystems. Our knowledge of the likely impacts of mining them is limited to inferences from natural disturbance events and some very limited test disturbances at a single site. Critical to the conservation debate will be the degree of interest in mining inactive SMS deposits, which can be a hard substrate or even sedimented system.

Effects of deep-sea mining on seamounts

The third type of deep-sea mining for which we need to consider ecological impacts is the mining of cobalt-rich crusts, which occur on seamounts. There is quite an intensive history of ecological work on shallow seamounts that sustain commercially viable fisheries[148,149]. However, cobalt-rich crusts are in general limited to deeper waters from 800–2,500 m depth, with likely mine sites being so-called ‘guyots’, flat-topped seamounts with a high ore grade and enough surface area to be commercially viable[150].

Regarding the geophysical impacts of cobalt-rich crust mining, there has been only very limited exploration, drilling and environmental survey with the exception of some trial mining on Takuyo-Daigo Seamount in the Japanese EEZ[151]. There are currently three contracts for mineral exploration at cobalt-rich crusts in international waters[152]. Public information on the extent of the contract area (and hence likely magnitude of seabed impact) is available only for the Korean and Japanese contracts, both comprising 3,000 km^2 (the Japanese contract is split into 150 20 km^2 blocks). The technical aspects of these operations remain either unknown or unpublished, but a reasonable assumption is that they would follow a system of dividing a crust region into mineable regions of an areal extent of about 260 km^2 for a 20-year mine site (13 4 x 5 km blocks)[150]. The actual area for exploration of these potential blocks might be about five times the area, so a model mining exploration site for cobalt crust might consist of 18 x 10 x 10 km blocks, conservatively assuming most areas of exploration are later deemed not suited to extraction (Figure 5). The principal geophysical impact would be the disaggregation of the mineralised crust through sub-sea cutting machines[153].

Biologically, seamounts are often described as hotspots of biodiversity[154], where the physical presence of the seamount itself diverts ocean currents that supply food and nutrients otherwise absent from the deep sea. Such relatively high productivity supports demersal and pelagic fish populations and benthic suspension feeders, such as corals and sponges, which in turn create habitat for a diverse invertebrate community. A global survey of bathymetric data identified 33,452 seamounts arising >1,000 m off the ocean floor, the vast majority of which are completely unexplored for biodiversity[155]. Benthic seamount communities typically comprise long-lived, slow-growing and fragile invertebrates, such as corals and sponges, with low tolerance to physical impacts[156]. Seamounts have been described as centres of endemism[157], stepping-stones for dispersal[158] and ‘vulnerable marine ecosystems’[159]. A review of cobalt-rich crust seamounts in the central north Pacific showed that there is high species turnover between seamounts in a region of potential mining interest[160]. Studies of corals on seamounts in the north Pacific have shown evidence for high levels of endemism[161,162]. Together this points to a relatively clear picture that seamounts are vulnerable ecosystems with a high degree of potential biodiversity value.

The mining of 260 km^2 of a guyot in the west Pacific[150] would clearly result in the near complete removal of the benthic fauna within a directly mined area (Figure 5). However, experimental studies are almost completely lacking, with only a single study to date[151] that reported, somewhat counterintuitively, that sessile suspension feeders were unimpacted by a small test mining event, but mobile swimming species were reduced in number in the disturbed areas. The only other known impacts relevant to crust-mining are based on studies of recovery following seamount fisheries[163]. While these are only partially relevant, given that seamount fisheries occur in much shallower water than proposed mine sites, these data suggest that recovery from trawling will take decades to centuries, with a high degree of uncertainty. The most critical impact of seamount-mining is likely to be the potential for biodiversity loss, considered further below.

In summary, similar to vent systems, seamounts are island-like systems with likely high degrees of endemism and potential for biodiversity loss. Of the types of deep-sea mining, they are the most recent to be suggested for exploration, and as such there is very limited data on the actual effects of test mining or recovery timescales.

Effects of deep-sea mining on pelagic ecosystems

While the benthic effects of mining nodules, SMS and cobalt crusts are likely to be completely different, one aspect of deep-sea mining that links them all is the potential for impacts in midwater (Figures 3 and 6), which is derived from the need to remove mud or mineral-rich water (dewatering) from the ore by the surface processing ships[164]. This discharge may return to the seabed, but some industry contractors are suggesting discharge in the ocean’s midwaters. In the case of nodule mining, this extends potential impacts from just the benthic system into the pelagic realm. Modelling of midwater sediment plumes suggests that they will extend for tens of kilometres and could affect 1,500–15,000 km^3 of seawater annually[165]. Aside from a small scale scientific experimental midwater plume discharge[166], there has only been one mining vehicle test that lifted nodules and created midwater discharge at ~1,200 m[107]. Empirical monitoring of this plume was conducted in the NORI-D CCZ contract area, but the results are not yet published. As such, current estimates of the effects of mid-water plumes are not based on experimental observations but on predictions using biological baseline knowledge and modelled particle dispersal and plume dynamics.

Some aspects of midwater ecosystems are well studied globally, for example the daily vertical migration of a portion of the fauna that is a significant source of vertical carbon flux[167]. However, specific baseline information on the pelagic ecosystem in the main regions of mining interest are largely lacking. In general, the eastern tropical Pacific harbours a very strong midwater oxygen minimum zone in the mesopelagic that vertically structures zooplankton assemblages[168] and is home to many endemic crustaceans and fishes[169]. Microbial assemblages are also vertically structured across the entire water column with distinct epi-, meso- and bathypelagic components[170]. Acoustic measurements across the CCZ showed that, in the eastern CCZ with a more pronounced oxygen minimum zone, vertical migration is stronger and that mean daytime depths of backscatter (a proxy for animal biomass) are shallower[171].

Seamounts that protrude into the mesopelagic often have zooplankton and micronekton communities similar to neighbouring offshore waters, but some taxa tend to be found only in association with seamounts or islands[172,173]. Seamounts increase or decrease the abundance of pelagic animals and may intensify links between surface waters and near seafloor ecosystems through predation by seafloor demersal species[174,175]. No studies of mesopelagic communities above seamounts targeted for mining have been conducted to our knowledge.

As the discharge plans from realistic mining scenarios are still unknown, there is the potential for impact from all three resource types on bathy- to abyssopelagic ecosystems (1,000 m to just above the seafloor at abyssal depths) through midwater discharge or advection of discharge near the seafloor into neighbouring bathypelagic waters. Certain taxa of fishes, shrimps[176] and also zooplankton[177] are often found in these very deep zones but only rarely or not at all in the mesopelagic[178]. Visual surveys using remotely operated vehicles clearly show the importance of gelatinous forms[179,180] and a water column environmental DNA (eDNA) study in the western CCZ APEIs came to a similar conclusion[181]. Although most studies find a rather low abundance and biomass over topographic features such as the mid-Atlantic Ridge[182,183] and even over the abyssal plain[184], they increase near the seafloor. Waters just above the seafloor are also home to larvae of many benthic species whose composition varies seasonally[185]. Despite these important studies, a recent survey of biodiversity revealed the bathy to abyssopelagic depths as the least studied in the oceans[186].

Hypothetically, direct physiological impacts on pelagic life from discharge could include respiratory distress from clogged gills, reduced visual communication from turbid waters, reduced feeding caused by dilution of organic particles with inorganic sediments, and toxicity from released metals[164]. Few studies provide empirical data on such potential impacts, and the spatial and temporal scales of potential impacts remain uncertain because of the lack of data on plume characteristics. One study on the helmet jellyfish (*Periphylla periphylla*) with a wide depth distribution exposed the animals to sediments in the lab, resulting in excess mucous production, increases in metabolic demand and the upregulation of a number of genes associated with wound repair[187]. Particles released from a nodule collector test at ∼1,200 m overlapped in size with naturally occurring detrital particles that form the base of the zooplankton food web[188]. Meta-analytical efforts suggest sediment effects will be linked to relative increases in sediment concentration[189] and potential pelagic impacts need to be constrained because they may directly impinge on ecosystem services including fisheries[184] or risk endangered or protected species[190,191]. In summary, empirical studies will be required to further understand if impacts of mid-water mining discharge on pelagic communities are meaningful, a requirement in exploration guidelines where midwater discharge is planned[99].

Potential loss of biodiversity caused by deep-sea mining

In this review, we distinguish the ecological impacts of deep-sea mining, such as changes in species abundance and community composition from which an ecosystem could potentially recover, from biodiversity loss, which we use here in its strictest definition of extinction. Reducing biodiversity loss is Target 1 of the 2030 targets set out in the Kunming-Montreal Global Biodiversity Framework[192], adopted by the 196 parties to the Convention on Biological Diversity. There is a clear policy stipulation to ''bring the loss of areas of high biodiversity importance, including ecosystems of high ecological integrity, close to zero by 2030''. While we do not comment on policy here, a reasonable scientific question is how compatible deep-sea mining may be with such targets. In terms of the Global Biodiversity Framework, there are two aspects to this discussion: first, what is the risk of biodiversity loss under proposed mining scenarios in abyssal plains, hydrothermal vents and seamounts? Second, is there a scientific basis to classify any of these potential habitats as areas of 'high biodiversity importance' or ecosystems of 'high ecological integrity' as defined by the framework?

Regarding the first question, understanding the risk of biodiversity loss requires a sound taxonomic understanding of communities to species-level, including biogeographic knowledge of species' ranges[193]. The last twenty years have seen a revolution in our knowledge of species identity and distribution based on DNA sequence data[194], and a significant increase in deep-sea taxonomic studies[195–198]. In the abyssal ecosystem of the CCZ, total animal biodiversity is estimated between 6,000–8,000 species, of which only 436 are named; of these, 23% have type localities from outside the CCZ[199]. In terms of available habitat, abyssal regions (3,000–6,000 m) globally make up a region of 307M km^2, approximately 54% of the planet's solid surface and of this 149M km^2 is thought to be sedimented abyssal hills, and 101M km^2 of true abyssal plain[3]. Thus, as a proportion of the abyssal plain, the entire CCZ (including its hills) makes up about 2% of the abyss globally.

With this in mind, what proportion of animals living in the CCZ also inhabit these other parts of the abyss? Based on taxonomic descriptions, which may include cryptic species, the 23% of species that have been described from outside the CCZ[199] likely do, but we have no information about the remainder. For the non-CCZ abyssal zone, we have only isolated sampling points, and several entire basins are completely unsampled. Evidence from DNA-barcoding-based studies[64,76] shows that the ranges of common species in the CCZ extend both across it and into other ocean basins. However, these studies have been focused on a fraction of the fauna, and the majority of species have only been recorded once with no range information, a pattern consistent with most deep-sea ecological datasets[200]. Thus, given the observation that abyssal plain fauna can have extensive basin-wide ranges, and that the 98% of the abyssal plain outside the CCZ is effectively unsampled, we are left with an absence of evidence regarding the potential biodiversity loss in the CCZ from nodule mining. There are two conceivable scenarios: on the one hand, based on the evidence we have from pan-ocean and inter-ocean abyssal species ranges for a small subset of taxa, we can extrapolate the same pattern to other abyssal taxa. This would lower the risk of biodiversity loss. On the other hand, there is strong evidence for habitat and biogeographic boundaries in the abyss[50,201] that can drive dramatic shifts in species composition[58], and hence potentially reduce ranges, increasing the risk of biodiversity loss. Further data are needed to test these scenarios.

By contrast, our understanding of the risk of biodiversity loss at vents is much clearer. Active hydrothermal vents are an extremely rare habitat globally, estimated to be less than 50 km^2 in total area (<0.00001% of Earth's surface)[126]. The species that have adapted to and are dependent on hydrothermal conditions are highly endemic: most vent species are not known from other habitats, and they typically exhibit further regional endemism in vents globally. This has enabled a much more rigorous assessment of potential irreversible biodiversity loss.

Using the IUCN 'red-list' criteria, for instance, 71 of 184 vent molluscs have been assessed as 'Endangered' or 'Critically Endangered', primarily in the Indian and West Pacific Oceans[202]. Increasing research efforts at hydrothermal vents are likely to discover more unique and endemic species, such that the more data we obtain, the greater the overall extinction risk.

Increasingly, biodiversity and conservation studies do not only focus on the number of species, but also include phylogenetic diversity and evolutionary distinctness[203]. Although hydrothermal vents may harbour many fewer species than abyssal sites, it is likely that their phylogenetic novelty will be higher; for example, several genera and families are exclusively found in vent ecosystems. The same may also hold for their functional diversity. Another complication is that SMS mining is likely to at least attempt to target inactive vent sites[204], with a potentially different, and for the most part unknown, faunal composition[144]. Our knowledge of inactive vents is currently inadequate to predict biodiversity loss.

Similar to vents, seamounts have been thought of as hotspots of endemism, as well as phylogenetic and functional diversity[154,157]. Some of these paradigms have been questioned[205], in particular the case of endemism, which is critical to understanding biodiversity loss. However, there is strong evidence for endemism in a number of well-studied seamounts, such as the North Pacific chains[161]. One challenge is the very large number of seamounts that have never been sampled. Some lessons can be learned from studies of shallower fished seamounts, which do show conclusively that the resident communities are highly sensitive and vulnerable to disturbance[205]. Given the current weight of evidence, it can be surmised that the risk of biodiversity loss at seamounts is not as well established as at active hydrothermal vents but is better understood than at abyssal ecosystems.

In the context of the Global Biodiversity Framework, it is necessary to determine the status of deep-sea mining regions with Target 1 — are regions at risk of biodiversity loss through mining areas of 'high biodiversity importance'? This is beyond the scope of this review, but a scientific approach for this has been attempted for seamounts and vents under the Convention on Biological Diversity's Ecologically or Biologically Significant Areas framework[206,207]. Both ecosystems would appear to meet many or all of the framework's criteria. For abyssal ecosystems, however, neither the risk of biodiversity loss nor their status as areas of 'high biodiversity importance' is established. If required, policy decisions on abyssal ecosystems in the context of the Global Biodiversity Framework will have to be made with a current absence of evidence and the associated risks on this issue.

Conclusions

Abyssal plains, hydrothermal vents and seamounts are completely different and independent ecosystems and should be considered separately in discussions of the environmental impacts of deep-sea mining. Furthermore, mining at hydrothermal vents could target active vents, inactive vent chimneys or potentially sedimented environments — three different types of ecosystem within one type of deep-sea mining target that may have quite different degrees of sensitivity to disturbance. An additional separate and poorly studied potential impact of any type of deep-sea mining is that of surface or mid-water discharge, affecting yet another completely different ecosystem.

Within all of these ecosystems, there are two main types of impact: impacts on the ecology (e.g. faunal density, community composition, life history or functional integrity) and biodiversity loss (extinction). For abyssal ecosystems, based on several empirical studies, an understanding is emerging of the impacts on ecology, including decadal-scale recovery processes, but the potential for biodiversity loss is not yet possible to predict, owing to insufficient taxonomic data. Some studies suggest that abyssal species have broad ranges, while others suggest significant biogeographic barriers. As the ISA develops the final version of a new 'Mining Code' to guide commercial extraction at nodule provinces, targeted studies within the protected regions of the CCZ are likely to be the best avenue to address this significant risk.

By contrast, for hydrothermal vents and seamounts, there are very limited data on the ecological impacts, but there is clear evidence of the risk of biodiversity loss owing to the isolation of the ecosystems and their high degrees of endemism. If vents and seamounts were to be classified as Ecologically or Biologically Significant Areas under the Convention on Biological Diversity, deep-sea mining at these sites would not be scientifically compatible with the Kunming-Montreal Global Biodiversity Framework.

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DECLARATION OF INTERESTS

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