statement

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# Deep-Sea Mining: assessing evidence on future needs and environmental impacts

## Contents

## Executive summary


The International Seabed Authority (ISA) organises and controls activities related to mineral resources in 'the Area' (defined as the seabed, ocean floor, and subsoil beyond the limits of national jurisdiction). The ISA has awarded exploration contracts for minerals in the Area since 2001 and is now developing a mining code for exploitation. While the ISA has the mandate to ensure the effective protection of the marine environment from harmful effects that may arise from mining activities, there is debate about the level of harm that might be caused by mining and whether the draft regulations are robust enough to meet that mandate and provide effective control.

Several European countries are sponsors of mining contracts with the ISA and Norway is planning to exploit minerals within its own exclusive economic zone and extended continental shelf. Policy-makers must thus assess whether economic pressures to extract minerals from the deep sea are compatible with the protection of marine ecosystems and their biodiversity. To inform current debate in the European Union and more broadly, the European Academies' Science Advisory Council (EASAC) has assessed the implications of the latest science and issued this Statement.

There are three main sources of deep-sea minerals: **polymetallic or manganese nodules** are located in abyssal plains, with much focus on the Clarion-Clipperton Zone in the Pacific Ocean; **cobalt-rich ferromanganese crusts (CRCs)** form at the flanks of seamounts; **seafloor massive sulfides (SMS)** deposits are found near active and inactive hydrothermal vents. Composition differs between these but primary economic targets are manganese, cobalt, nickel, and copper for the first two sources, and copper, zinc, silver, and gold for SMS deposits.

The narrative for deep-sea mining often anticipates shortages in the metals required for the energy transition, with assertions that increased demand in 'green technologies' cannot be met from terrestrial sources. We examine demand forecasts, the potential for recycling and for technological innovation to change future metal demand, and find that there is much uncertainty about the future balance of supply and demand. The argument that deep-sea mining is essential to meet the demands for critical materials is thus contested and does not support the urgency with which exploitation of deep-sea minerals is being pursued. There remains much potential for policy to prioritise a circular economy, support innovation, and minimise continued dependence on the linear economy's focus on extracting virgin materials from nature. **The European Commission's policy on critical raw materials and its regulation on recycling electric-vehicle batteries are welcome first steps and should lead to a framework that encourages recycling for all renewable energy systems.**

Deep-sea mining may affect the environment and biodiversity in several ways. We summarise current knowledge on deep-sea biodiversity and the likely impacts of mining. Major knowledge gaps remain on ecosystem structure and function, the species present, how they interact, and their tolerances and resilience. Even so, on the basis of existing information it is clear that mining will have the following effects:

- Biota in the areas directly mined at the seabed will be killed.
- Sediment discarded on site is likely to be inhospitable to recovery for decades to centuries in the case of nodule mining, and decades for SMS mining.
- Loss in the structure of habitats may lead to indefinite reductions in biodiversity.
- The collateral ecological damage through sediment plumes will expand the area of impact at the seabed and in the water column.
- Noise, light, and vibration are other factors that may impact biota around the mining site.

**Such impacts may extend from hundreds of thousands to millions of square kilometres if mining approaches its planned scale to recover millions of tonnes of ore from nodules or from CRCs, but be more localised in the case of SMS deposits.**

We discuss the international regulatory regime and point out that the treatment of environmental impact remains under development. The ISA has a duty to ensure '*effective protection for the marine environment from harmful effects of seabed mining activities*'. Avoiding '*serious harm*' also features in the Law of the Sea Convention. Destruction of large areas of the seabed may seem 'serious' to the lay observer, but debate is still underway about what level of environmental damage would be regarded as 'serious' and trigger refusal of a contract. The ISA is developing environmental thresholds and is establishing subgroups on threshold values for turbidity, toxicity, and

noise/light disturbance. However, there are no actions at present to develop other criteria, including measures of biodiversity impact and habitat destruction.

The lack of a consensus on what constitutes 'serious harm' and the current lack of quantitative thresholds limits the ability of ISA to effectively protect the marine environment and **supports the current position of the European Commission, the European Parliament, and several Member States in advocating a moratorium until ecological consequences can be properly understood, measured and controlled. There is also a strong case that especially sensitive areas such as active hydrothermal vents with their unique biological characteristics should be out of limits to mining.**

To meet the duty to protect the marine environment, regulation should be precautionary and stepwise; each step should be subject to explicit environmental management goals, monitoring protocols, and binding standards to avoid serious environmental harm and minimise loss of biodiversity. An improved understanding of environmental impacts should ultimately lead to a duty on the ISA to properly assess whether any economic benefits of mining that accrue to humankind are justified by the high risk and the long-term nature of the harm to the environment and its ecosystem services, through international consensus. Proper environmental assessments are challenging for the ISA in view of the limited in-house environmental expertise, and means of overcoming this are required.

Deep-sea mining should also be assessed against the backdrop of recent international decisions on marine biodiversity within the Convention on Biological Diversity and the recent legally binding agreement on the protection and sustainable use of marine biodiversity in areas beyond national jurisdiction (the BBNJ Agreement). We point to the danger of conflicting objectives if the ISA focuses on exploitation at the expense of environmental and biodiversity protection. There have been suggestions that marine biodiversity should be seen as part of the 'common heritage' of humankind that the ISA seeks to protect in its assessment of mining proposals.

Public debate is often framed as offering deep-sea mining as an essential part of the energy transition in its provision of some of the metals required in clean energy technologies, or as the lesser of two evils when compared with terrestrial mining. This narrative may be in response to some companies' pledges not to use deep-sea mined resources and to argue that deep-sea mining should be included in 'green' investment taxonomies. **We discuss the validity of such claims and find them misleading, and note also that deep-sea mining lacks the mitigation and remedial measures available to terrestrial mining.**

Finally, we point to the substantial proportion of deep-sea mineral resources that are within the exclusive economic zones of coastal states, and Norway's proposal to evaluate their own deep waters for SMS mining. There is an obligation that any national pollution standards should not be less than those applied internationally, but because these have yet to be decided, early actions by individual countries could provide valuable data on how to protect the marine environment. Such countries should be encouraged to share data and experience generated with the international community and ISA. In the case of Norway and other SMS mining plans, while the areas impacted by SMS deposits are likely to be smaller than for the collection of nodules, acid generation and the release of toxic metals may be more likely.

## 1 Introduction

As the global population continues to rise and governments remain dedicated to growth in consumption in a linear economy, demand for raw materials continues to rise. Consumption of metal ore almost quadrupled between 1970 (2.65 billion tonnes) and 2019 (9.74 billion tonnes).[1] At the same time, recycle rates remain low for all but a few easily separated and recovered metals such as iron and lead, with even copper and nickel recovery accounting for less than 20% of demand (EC 2020a). The inevitable increase in humanity's demand on the planet's natural resources described in EASAC's report on transformational change (EASAC 2020) continues.

While overall demand continues to rise, the energy transition from fossil fuels to low-carbon sources is increasing demand for certain metals essential for manufacturing solar panels, electric motors, batteries, and other 'green technologies'. Forecasts (e.g. EC 2020b; IEA 2022) foresee a gap between existing mine production and demand, leading to a continued search for new sources. This is against the backdrop of declining ore richness and increasing pressures to protect remaining natural areas of the planet from further destruction and to restore biodiversity in line with recent outcomes of the Convention on Biological Diversity (CBD 2022).

[1] https://www.resourcepanel.org/global-material-flows-database

Minerals found in the deep sea have been seen as a potential source of certain metals ever since they were first discovered in the scientific expeditions of HMS *Challenger* (1872–1876). Subsequently, initial work on the distribution of minerals in deep waters and research on their extraction has been done by commercial enterprises and governments. The International Seabed Authority (ISA) was established in 1994 under the UN Convention on the Law of the Sea to organise, regulate, and control all mineral-related activities in waters outside national jurisdiction ('the Area') for the benefit of humankind. In 2001 the ISA signed the first contract for exploring polymetallic nodules;[2] by 2023, it had signed 19 contracts for nodule exploration, mainly in the Clarion-Clipperton Zone (CCZ) of the Pacific Ocean, covering more than 1,250,000 km$^2$. Contracts have also been signed to explore cobalt-rich crusts (CRCs) and seafloor massive sulfide (SMS) deposits. Regulations for exploitation remained under development, but in June 2021 Nauru invoked the '2-year rule' that sets a target for the ISA to agree regulations for exploitation (the mining code) by 9 July 2023.[3]

Within Europe, the European Commission (EC) recognises the importance of secure and sustainable access to critical raw materials; in earlier assessments (e.g. EC 2018), it funded studies to explore the benefits, drawbacks, and knowledge gaps associated with deep-sea mining,[4] and research into the environmental impacts.[5] Recently a new Critical Raw Materials Act has been proposed to lessen external dependence on critical raw materials (EC 2022a). At the same time, concern about environmental, biodiversity, and governance issues related to deep-sea mining has already led the European Parliament to call for a moratorium on commercial extraction, and the EC in its 2022 communication on governance (EC 2022b) committed to (*inter alia*) '*Prohibit deep-sea mining until scientific gaps are properly filled, no harmful effects arise from mining and the marine environment is effectively protected*'. At the same time, Norway is evaluating plans for deep-sea mining in its continental shelf.

There is thus some urgency in assessing whether economic pressures to extract minerals from the deep sea are compatible with the protection of marine ecosystems and their biodiversity. EASAC's council thus decided to assess the implications of the latest science in order to assist policy development in European Union institutions. This Statement has been prepared by EASAC's Environment and Energy Steering Panels and subject to external peer review. We first consider the need for additional sources of the metals obtainable from deep-sea mining and the state of knowledge on its environmental impact, before discussing the policy options that emerge from or are consistent with the science.

## 2 Demand and supply uncertainties for critical materials

### 2.1 Metals involved and their need

There are three main sources of deep-sea minerals under consideration. Compositions vary between these types and with location.

1. **Polymetallic or manganese nodules.** The chemical composition of nodules varies with location, but the main constituents of interest are nickel (1.3%), copper (1.1%), and cobalt (0.2%) in addition to manganese (28%), with rare-earth metals and lithium, molybdenum, platinum, titanium, and tellurium at trace levels (Hein *et al.* 2013; Kuhn *et al.* 2017). The largest of these deposits in terms of nodule abundance and metal concentration occurs in the Clarion-Clipperton Zone (CCZ) in the Pacific Ocean at water depths below 3,500 m. It is considered that, to be of economic interest, the abundance of nodules must exceed 15 kg/m$^2$ (Joseph 2017).

2. Some ferromanganese crusts occurring on seamounts contain up to 0.6% cobalt and are known as **cobalt-rich crusts (CRCs)** and contain manganese, copper, and nickel. Lithium, thallium, tellurium, yttrium, bismuth, rare-earth elements, niobium, and tungsten are present at trace concentrations. Seamounts range from small hills to peaks that are thousands of metres high. The crusts are deposited on bare rock surfaces at very slow rates, so the oldest seamounts generally have the thickest crusts but still only surface deposits up to 10–20 cm in thickness. The Prime Crust Zone is in the Northwest Pacific.

3. **Seafloor massive sulfides (SMS)** are deposited at **hydrothermal vents** and contain copper, zinc, silver, and gold as primary mining targets.

A prediction of the most likely deposits of these minerals is shown in Figure 1 (Miller *et al.* 2018).

[2] To the Polish Interoceanmetal Joint Organization and to the Russian Federation's JSC Yuzhmorgeologiya.
[3] Under this provision, once notified of a proposal to submit an exploitation application, the ISA must finalise a set of regulations governing the exploitation of minerals within 2 years, or be obligated to consider and provisionally approve it.
[4] The Blue Nodules industrial collaborations project aimed to develop an industrially viable polymetallic nodule business case, and the Blue Harvesting project aimed to improve nodule collector design to reduce environmental impact while maintaining production rate and efficiency.
[5] This includes the MIDAS project (https://www.eu-midas.net/) and work within the framework of JPI-Oceans 2 projects (MiningImpact1 and MiningImpact2; https://miningimpact.geomar.de/phase1; https://miningimpact.geomar.de/).

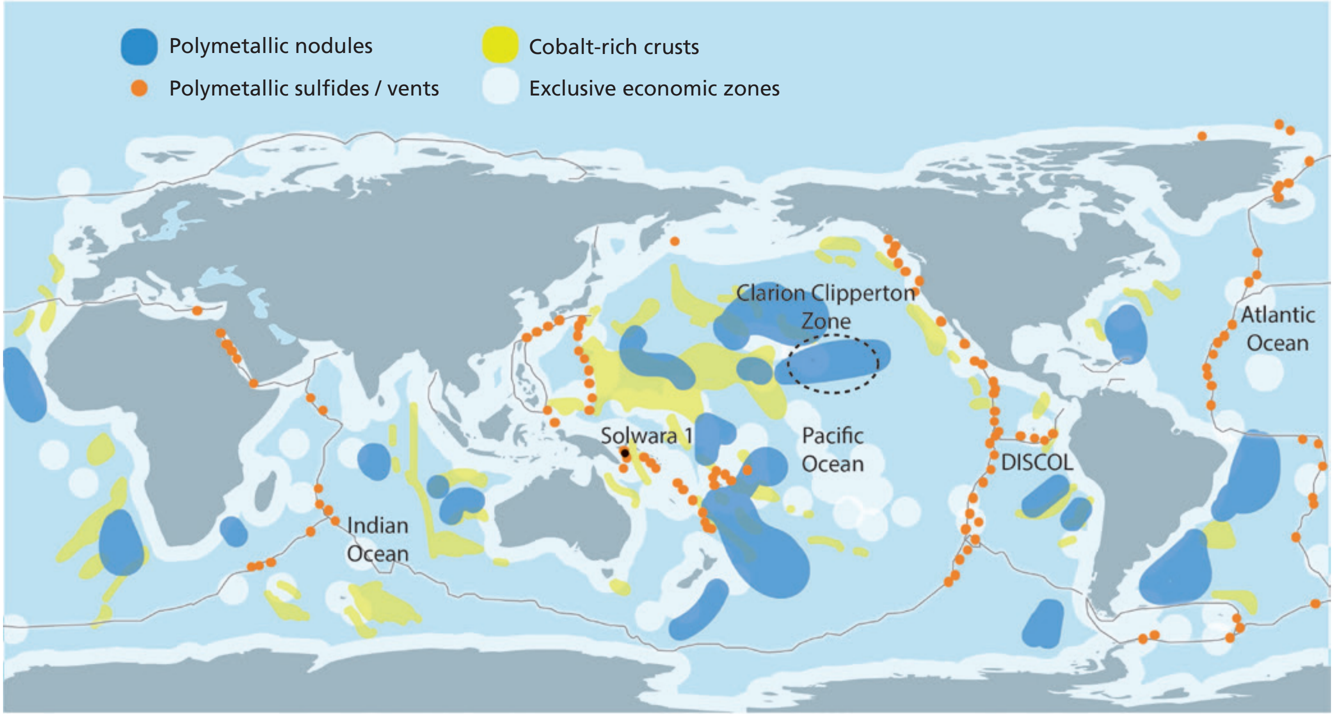



*Figure 1 Location of the three main marine mineral deposits: polymetallic nodules (blue); polymetallic or seafloor massive sulfides (orange); and cobalt-rich ferromanganese crusts (yellow) (Miller et al. 2018).*

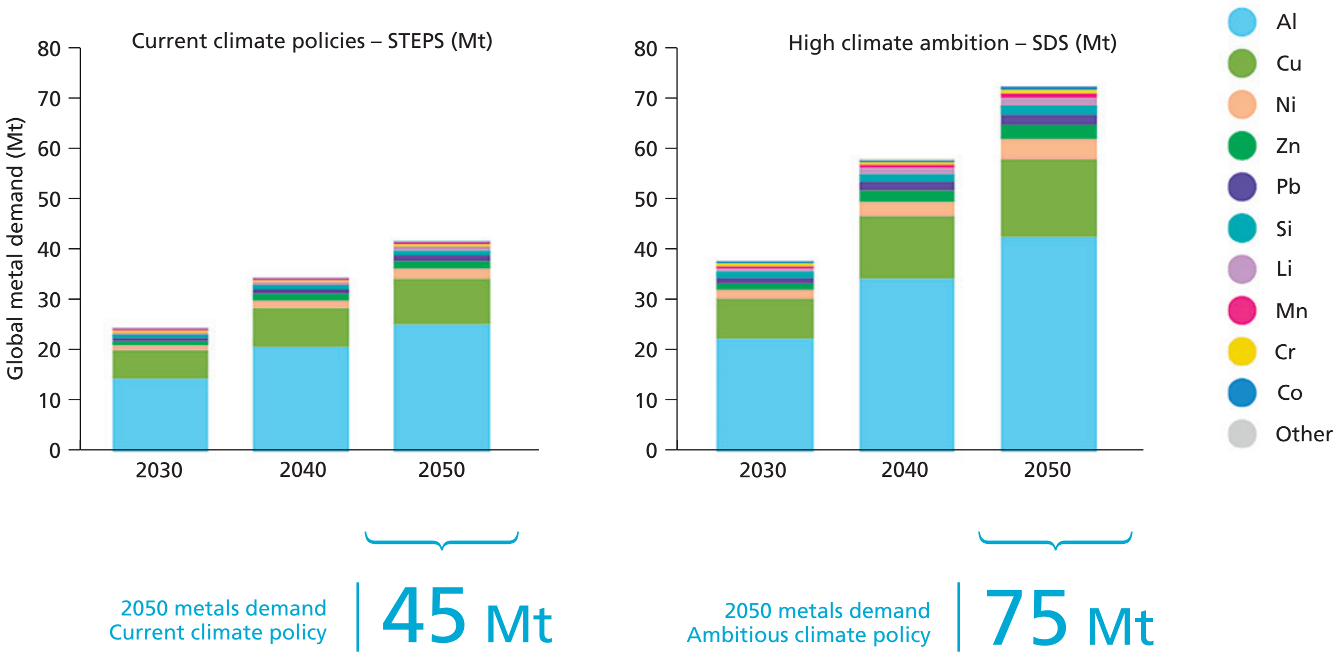



*Figure 2 Global metal demand for clean energy technologies (KU Leuven 2022) on the basis of current and ambitious climate policies. Abbreviations: Mt, million tonnes; SDS, Sustainable Development Scenario; STEPS, Stated Policies Scenario.*

Since the case for deep-sea mining often depends on shortages of the metals required for the energy transition, we consider the uncertainties involved. Industry-commissioned studies vary widely: for instance, KU Leuven (2022) saw demand for the main metals involved by 2050 ranging from 45 million to 75 million tonnes (Figure 2).

The IEA (2022) forecasts that demands from the clean energy sector will account for an increasing share of total demand: rising over the next two decades to more than 40% for copper and rare-earth elements, 60–70% for nickel and cobalt, and almost 90% for lithium. The rate of growth is expected to be very high, with demand for lithium growing more than

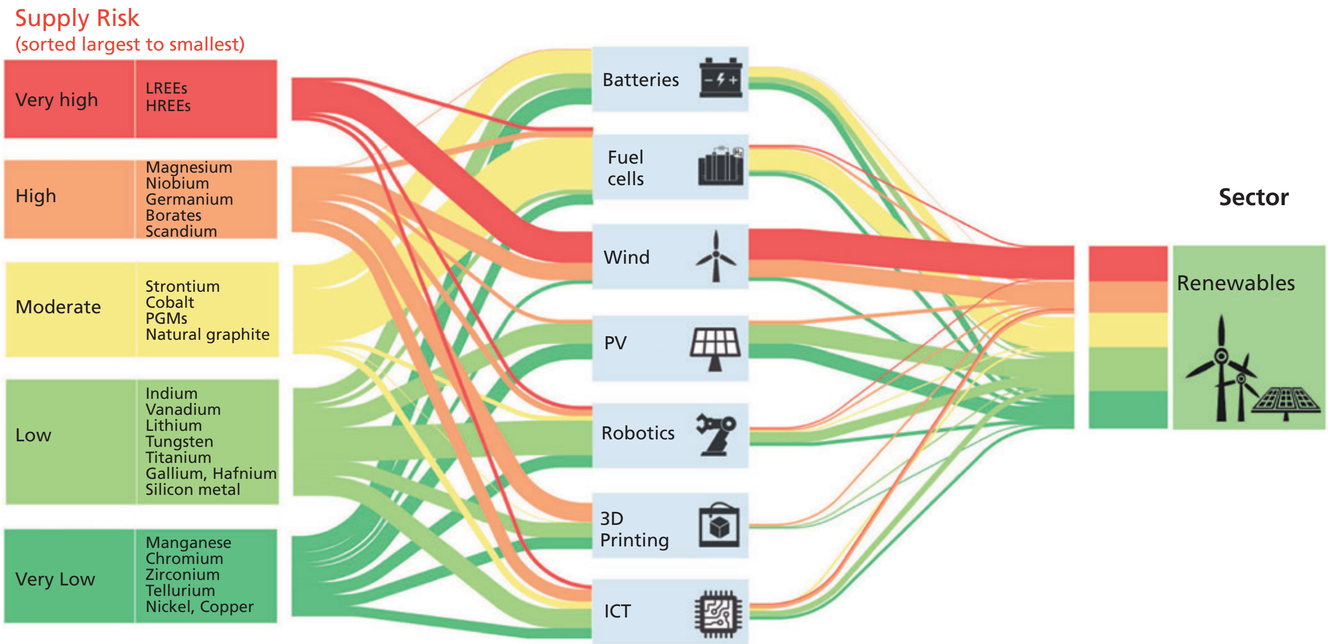



*Figure 3 Semi-quantitative representation of flows of raw materials and their current supply risks to the nine selected technologies and three sectors (EC 2020b). Abbreviations: HREEs, heavy rare-earth elements; ICT, information and communications technology; LREEs, light rare-earth elements; PV, photovoltaics.*

40 times by 2040, followed by graphite, cobalt, and nickel (around 20–25 times). This increasing demand is part of wider concerns about the availability of critical raw materials that also affect other industries such as information technology and defence. The European Commission has continued to adjust its list of Critical Raw Materials (EC 2020c; 2023), with associated supply risks shown in Figure 3.

It can be seen from Figure 3 that three of the main metals targeted in deep-sea mining (manganese, copper, and nickel) are considered to be of low supply risk while cobalt is moderate.

## 2.2 Potential for recycling to meet demand

The extent to which rising demand increases the need for virgin materials depends *inter alia* on the supply of secondary raw materials through recycling. Harvesting the Critical Raw Materials in the European 'urban mine' of end-of-life products will improve the resilience of crucial value chains, cushion volatile metal prices, and reduce the carbon footprint and environmental impact of the supply of raw materials (Hagelüken and Goldmann 2022). Despite the EU's focus o n the circular economy, the recycling rates for many Critical Raw Materials remain low.[6] Recycling technology and industrial capacities are available to recover cobalt and other battery metals with high yields, but only a small proportion of spent portable batteries reach these facilities. Globally, the amount of cobalt in up to 3 million electric car batteries is lost (Hagelüken and Goldmann 2022).

The potential for recycling is estimated (KU Leuven 2022) to be as high as 40% to 77% of Europe's clean energy metal needs by 2050; however, this would require early investment so that recycling capacity is available in time to process the anticipated exponential growth in batteries, wind generators, solar panels etc. at the end of their use. Bottlenecks need to be solved in collection and sorting operations, product design, and in preventing scrap leakage. Currently, electric-vehicle battery recycling is the subject of a new Regulation that includes both metal-specific minimum recycling rates for copper, cobalt, nickel and lithium as well as minimum recycled content for lithium, cobalt, and nickel in new batteries, with the aim of establishing a recycling framework in time for the huge increase in batteries at their end of life. But other major waste streams will emerge from solar panels, out-of-date wind generators, and the like. The 'Circular Economy Action Plan' published in March 2020 is an important framework within which specific initiatives should be developed (EC 2020d).

Meanwhile, research may offer new approaches. The European project REEgain found that microorganisms such as bacteria, algae, or fungi can absorb rare-earth elements into their cells; this could offer a means of

[6] Recycling's contribution to meeting materials demand is between 20–40% for tungsten, europium, yttrium, antimony, palladium, rhodium, and cobalt; 10–19% for titanium, iridium, magnesium, ruthenium and praseodymium; while 0–9% for all other Critical Raw Materials (EC 2020a).

extraction from e-waste (https://www.fh-krems.ac.at/en/research/projects/reegain/). Various plants accumulate metals (Nkrumah and van der Ent 2023). At the US Critical Materials Institute, rare-earth elements from high-powered magnets in electronic waste are extracted by membrane separation (https://www.ornl.gov/news/trash-treasure-electronic-waste-mined-rare-earth-elements). Sources for cobalt and lithium from seawater have also been evaluated.[7]

### 2.3 Technological uncertainties

Forecasting future demand is often based on extrapolating current technologies with assumptions about efficiency gains, but estimates differ greatly. For example, Habib *et al.* (2020), Hund *et al.* (2020), and Dominish *et al.* (2019) foresee demands of 68, 24, and 100 million tonnes respectively for the amounts of nickel required up to 2050. Yet transformational changes in a technology are not uncommon. With solar panels there are many different combinations of elements and platforms (crystalline versus thin-film), while batteries may undergo changes that reduce the demand for nickel and cobalt (for example to lithium–sulfur or lithium iron phosphate batteries), or for lithium itself (through the development of sodium ion cells). Meanwhile, batteries based on graphene aluminium-ion, iron-flow, and solid-state technologies may also reduce demand for current critical materials. Innovative approaches (e.g. perovskites and organic solar cells) promise a further reduction of materials use or higher efficiency (EC 2020b).

Projections also do not account for policy shifts that reduce dependence on personal vehicles, extensions in product life and reduced obsolescence, or higher recycle rates promoted by regulations. When such factors are considered and future innovations assumed to continue historical efficiency gains in metal intensity, Teske *et al.* (2016) and Månberger and Stenqvist (2018) calculated that terrestrial mineral reserves are sufficient to supply the metals needed for the renewable technologies required to meet the Paris Agreement targets by 2060. The perception that the metals provided by deep-sea mining are critical and scarce can thus be the result of inadequate consideration of the potential for future technological innovations.

## 3 Deep-sea resources and their exploitation technologies

### 3.1 Types of resource and metal production

As mentioned in section 2.1, there are three main types of deposit that are of interest to mining: manganese nodules, cobalt-rich ferromanganese crusts (CRCs), and seafloor massive sulfides (SMS). Petersen *et al.* (2016) estimated that sites most favourable for nodule mining cover 38 million km$^2$; for CRC mining, 1.7 million km$^2$; while sites most favourable for SMS mining cover 3.2 million km$^2$. The ISA (2022a) assessed the potential production of metals from deep-sea mining on the assumption that individual contractors may start seabed mining in about 2027. From then, the highest-production scenario (based on 12–18 parallel mining operations) is that, by 2035, 36 million tonnes (Mt) of nodules could be extracted each year, providing 356,400 tonnes (t) of copper, 444,600 t of nickel, 61,200 t of cobalt, and 9.2 Mt of manganese. The economic value of 3 Mt of nodules was valued at approximately US$430 million for copper, nickel, and cobalt, and some US$425 million for manganese. At 2035's upper forecast, the total value of mined materials could be more than US$10,000 million each year. In such a scenario, sources of deep-sea mining could account for 50% of the current annual demand for manganese (18 Mt) and cobalt (0.12 Mt), 20% of current nickel demand (2.5 Mt), but only 2% of the larger demand for copper (17 Mt). Such estimates are, however, very sensitive to future prices and lower rates of exploitation (e.g. three or four parallel mining operations) are likely at current prices.

The ISA (2022a) study concluded that land-based sources could meet demand in all scenarios except those with the highest growth, so that deep-sea sources may lead to oversupply and price reductions, and/or land-based projects being abandoned. Should prices for one or more of the four main metals fall, this could result in seabed mining projects becoming sub-economic or unprofitable. There is thus considerable uncertainty about both the economic prospects and the associated disruptions in the many countries hosting land-based metal mines (Table 1). The latter must be considered because the ISA is obligated to operate an assistance fund derived from mining royalties to compensate for economic disruption in developing nations dependent on mining exports.

### 3.2 Recovering minerals from the deep sea

As shown in Figure 4, deep-sea mining involves four main stages: the initial mining of the target material in deep water; a riser system that lifts the material to a production vessel; initial dewatering and separation of sediment that accompanied the ore; and shipment of the ore concentrate to a shore-based processing facility to extract the metals contained.

[7] There is a potentially unlimited source of materials, such as cobalt and lithium, directly from seawater (Haji and Slocum 2019; Zhen *et al*. 2021) through passive adsorption technologies on existing unused offshore structures. Other means of extracting rare-earth elements from wastes such as coal fly ash or e-waste include a flash Joule heating process (Deng *et al*. 2022).

**Table 1 Country dependence on exports of copper, nickel, cobalt, and manganese**

| | Products' share in export revenues (%) | Products' share of GDP (%) |
|---|---|---|
| Exporters of copper products | | |
| Zambia | 56.1 | 18.7 |
| Democratic Republic of the Congo | 55 | 11.1 |
| Eritrea | 50 | 5.6 |
| Chile | 48.9 | 12.8 |
| Lao People's Democratic Republic | 34.4 | 7.7 |
| Mongolia | 26 | 15.9 |
| Peru | 25.8 | 5.1 |
| Exporters of nickel products | | |
| Madagascar | 20.3 | 3.7 |
| Zimbabwe | 15.6 | 3.1 |
| Exporters of cobalt products | | |
| Democratic Republic of the Congo | 24.3 | 4.8 |
| Exporters of manganese products | | |
| Gabon | 21.9 | 5 |
| Cumulative effect of exports of all affected metals | | |
| Mauritania | 12 | 4.8 |
| Namibia | 11.4 | 4.9 |
| Papua New Guinea | 10.6 | 4.3 |

Source: ISA (2022a).

Companies and consortia have developed remotely operated machines that would suck up nodules or excavate deposits before pumping them back to the surface several kilometres overhead. For instance, one group (Royal IHC) has designed a 16-metre-wide robot that would be able to gather about 400 tonnes of nodules per hour;[8] a Belgian company (DEME-GSR) conducted a pre-prototype collector test in spring 2021.[9] The Metals Company has just completed a test of a collector that extracted 4,500 tonnes of nodules from an 80 km length run in the CCZ.[10]

Box 1 describes the options for SMS mining in the case of the Norwegian proposal.

## 4 Environmental impact and mitigation potential

### 4.1 The deep-sea environment

Any mining operation (Figure 4) will have to work from the ocean surface to the seabed. So, assessing impacts requires an understanding of the ocean ecosystem: vertically from the ocean surface to the seafloor sediment; and laterally because of the mobility of species resident or passing through the affected areas, the potential spread of impacts through ocean currents, and species connectivities over long distances. This is illustrated in Figure 5 (UNEP 2022).

Within depths of about 200 m, light is sufficient to support phytoplankton that provide food for zooplankton and higher consumers. This is the photic zone; but as light fades with depth, the ability to support photosynthesis declines and ultimately ceases. Although insufficient to support photosynthesis, there is still enough light to see down to depths of about 1,000 m, which is called the dysphotic or twilight zone; below this comes the aphotic (or midnight) zone, where no light penetrates. All the depths under consideration for mining are in this last zone, so in a background of complete darkness.

Owing to the darkness, novel means based on luminescence or vibration sensitivity to detect movement have evolved to find a mate, catch prey, or avoid being caught. Many deep-sea fishes depend on underwater sound for communication during mating and possibly for navigation. Some species straddle all the above zones: sperm whales can go down to depths of 1,000 m, while some pelagic species have evolved to live and breed in the deep sea (e.g. Greenland Sharks are found as low as 2,000 m). Generally, the uniform cold, pressure, and stability are associated with very slow rates of growth and very long lifetimes (Greenland sharks live for 250–500 years; some corals for thousands of years).

Despite the lack of photosynthesis, deep-sea organisms obtain energy from the photic zone from dead material (ranging from dead plankton and other organic debris to dead whales) drifting down (so-called 'marine snow') but deep-sea microorganisms have also evolved means of harnessing the energy in chemical reactions. In the 1970s, it was discovered that bacteria have evolved to harness the chemical energy in the hot and mineral-rich waters discharged where tectonic plates meet, and thereby support rich local ecosystems. Various microorganisms transform elements such as carbon, sulfur, nitrogen, and hydrogen to biomass, forming the basis of a biodiverse food web. The fauna shows high degrees of specialisation depending on the food source and habitat. Some species use the mats of bacteria as a food source, but others exploit symbiotic relationships between bacteria and hosts. This supports snails, bivalves, shrimps, crabs, and tube worms that in turn support, for example, fish and cephalopods through predator–prey relationships.

[8] https://www.royalihc.com/mining/project-type/underwater-mining.
[9] https://www.deme-group.com/news/metal-rich-nodules-collected-seabed-during-important-technology-trial.
[10] https://metals.co/download/238787/?tmstv=1667943211.

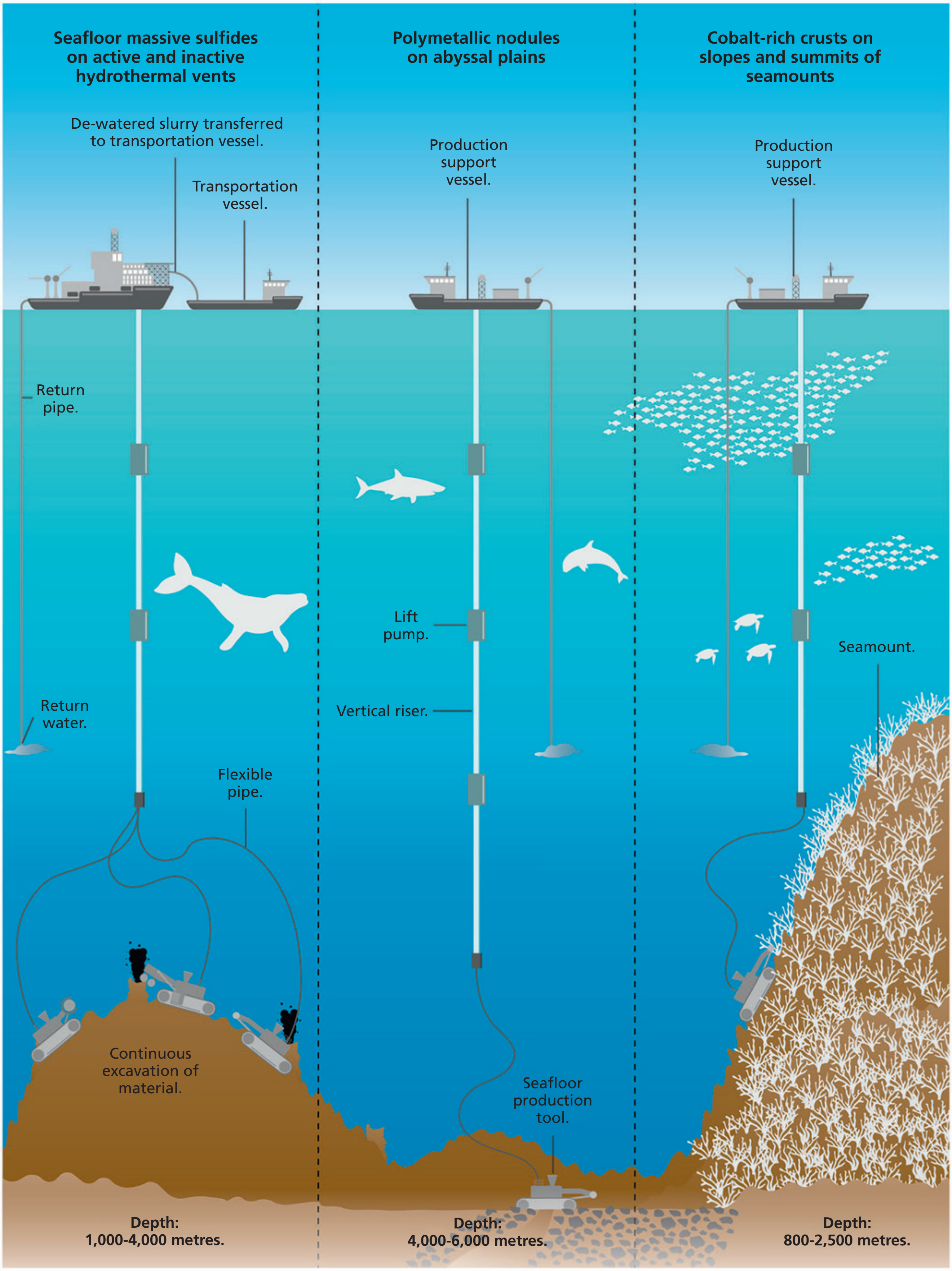
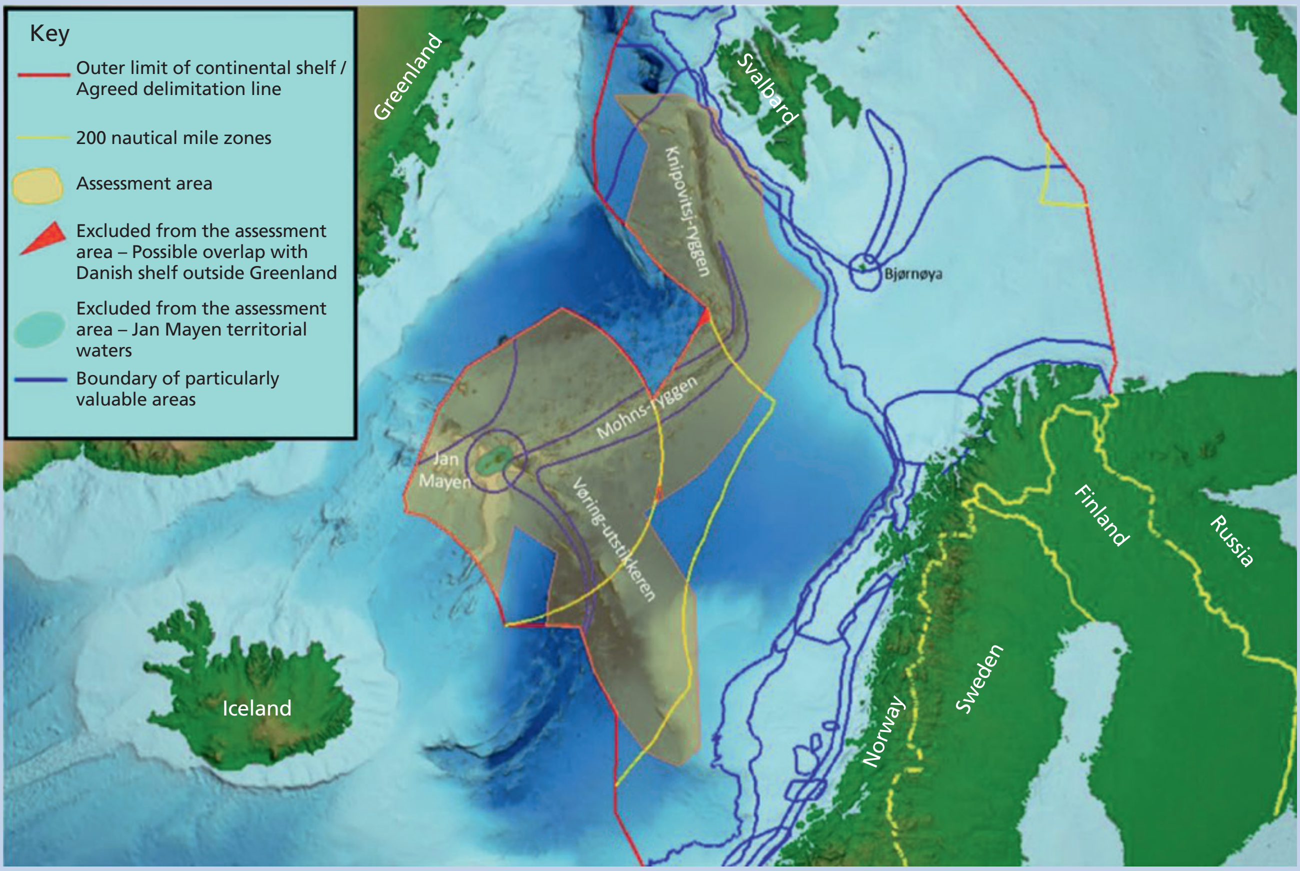



*Figure 4 The processes involved in deep-sea mining for the three main types of mineral deposit (Miller et al. 2018).*

**Box 1 The Norwegian options for SMS mining**

Mining of copper and zinc from massive sulfide deposits on land has a long tradition in Norway, with more than 100 Mt of ore from 10 major mines having produced 1.7 Mt of copper and 1.9 Mt of zinc, as well as lead, silver, and gold. Massive sulfide deposits in the Caledonian mountain chain are still regarded as having potential for new discoveries: https://www.ngu.no/sites/default/files/Focus_1_2022_MASSIVE_SULFIDES_IN_NORWAY.pdf

More recently, seabed minerals have been identified in Norwegian waters, primarily in the form of sulfides and CRCs (Box Figure 1); and in 2019, the Norwegian Parliament passed a Marine Minerals Act and is scheduled to vote on opening the Norwegian exclusive economic zone (EEZ) for commercial mineral exploration and extraction in 2023, pending an ongoing environmental impact assessment (https://www.npd.no/en/facts/seabed-minerals/environmental-impact-assessment/).




*Box Figure 1 Area under consideration for SMS mining; the area under consideration for investigation is in brown, encompassing 592,500 km$^2$, in areas typically of about 1,500 m depth but ranging from 100 m to 4,500 m.*

Considering the very different properties of SMS and CRC deposits, the two will probably require different technologies both for exploration and extraction. A critical uncertainty is the average ore grade, which is expected to be between 3% and 5%.

The grade of 5% was assumed in a study advocating exploitation by Rystad Energy (2020), with the ore containing primarily copper (78%), zinc (16.9%), and cobalt (5.6%). Proposals envisage individual mining projects extracting around 30 Mt of minerals over 15 years. A major selling point in the proposals is that it offers a means of switching Norway's offshore oil and gas engineering services to a marine minerals industry as demand for fossil fuels declines.

Bang and Trellevik (2022) calculated a range of scenarios in ore grade and projected a resource base of 1.8 to 3 Mt of copper, zinc, and cobalt, in which copper makes the most significant part. They found a discrepancy between academic and industrial expectations: academic calculations project a negative net present value, whereas industrial expectations project a positive one. These range from a loss of US$970 million to a gain of US$2.53 billion). Initial exploration costs associated with coring operations are a critical factor.

Away from some of the closely studied active vent systems, knowledge of biodiversity and ecosystem functions remains sparse owing to the vast areas involved and difficulty in sampling. New species are found on most surveys including some hitherto unseen life forms. Even though biota are sparse, biodiversity is high, with organisms ranging from the photogenic 'dumbo octopus', 'gummy squirrels', 'blue blobs', 'ping pong sponge', and immensely long siphonophores to possibly thousands of species of polychaete worms.[11]

Overall, the biology of the deep sea is characterised by high biodiversity, large numbers of rare species, highly adapted species, unique habitats, vulnerable ecosystems, and low metabolic rates associated with species longevity. Deep-sea ecosystems provide a range of supporting, provisioning, regulating, and cultural services (Thurber *et al.* 2014).

## 4.2 Environmental impacts

### *4.2.1 Overview*

The potential effects of mining processes on the marine environment have been the subject of many scientific papers (e.g. Levin *et al.* 2016; Van Dover *et al.* 2017; Boetius and Haeckel 2018; Miller *et al.* 2018; Jones *et al.* 2020; Duarte *et al.* 2021) and reviewed by Levin *et al.* (2020). Impacts can result from the following:

- Direct removal and destruction of seafloor habitat and organisms.
- Alteration of the substrate (e.g. loss of vertical topography and heterogeneity, altered texture).
- Sediment plumes from the mining site or from the vessel used to dewater and separate sediment from the slurry pumped up from the seabed. Sediment effects may arise from physical smothering and burial, or from clogging of respiratory, feeding, or olfactory organs and other physical damage (Drazen 2020), and extend beyond the mining area through dispersion of sediments.
- Disruption of biogeochemical processes (bacteria as the foundation of food webs depend on oxygen, methane, hydrogen sulfide, hydrogen, etc. and bioturbation), with possible implications for carbon flows.
- Disruption of the food web and ecosystem functions.
- Disruption of fragile biogenic habitats whose loss will reduce diversity of associated organisms.
- Released toxins (e.g. metal contaminants).
- Effects from light, vibration, and noise pollution at the seabed or surface operations.
- Wider ecosystem effects arising from habitat or population fragmentation; disruption of species and genetic connectivity (e.g. by larval dispersal).

Impacts differ between the three mining approaches and are summarised in Box 2.

In short, as described in Box 2, direct impacts of the mining process inevitably destroy the biota over wide areas; however, the extent and nature of disruption may differ. With nodule extraction, removal of the attachment points in muddy sediments for some species[14] represents a structural change that will inhibit any recolonisation that could otherwise have taken place. Sediment stability (or lack of it) may also delay recolonisation of sedimentary organisms by decades to centuries. Effects from the sediment plumes are critical because, depending on the number and distribution of areas mined in a contract, they could extend impacts to areas several times those actually mined.

In the case of CRC, large areas are also required to be mined owing to the thinness of the ore deposit, and mining may have to take place on multiple locations, because the deposit sizes on individual mounts are limited. Mining will destroy the fauna, with recolonisation hampered by the low reproduction rate of the resident fauna and structural or geochemical changes in the habitat.

Mining of SMS requires less area but impacts will differ depending on whether the deposits contain active vents. Mining is likely to focus on inactive deposits that host a background fauna containing species such as those found on seamounts. Active vents containing their assemblages of unique and rare organisms, and which may be classified as vulnerable marine ecosystems by the Food and Agriculture Organization, are present in many SMS deposits of commercial interest, and would be destroyed unless care was taken to avoid them. The sulfides exposed by mining will also generate acid and release potentially toxic metals, so the impact of plumes could be an issue if they affect vulnerable habitats away from the mine site.

### *4.2.2 Sediment plumes*

Plumes from the collecting device or from the surface vessel may cause a secondary impact. In the normally high-clarity water column, even very low concentrations of sediment may impact fauna that has evolved to capture the sparse marine snow or microzooplankton as their food. How far sediment plumes spread will depend on many factors related to the nature of the sediment and the hydrographic conditions of the discharge area, and may extend the impact area well beyond

[11] A recent survey by Bonifácio *et al.* (2020) of five areas in the CCZ discovered that 49% of the species identified were found in only one location, suggesting that there were very large numbers of species (between 498 and 240,000) across the whole CCZ.

[12] http://www.eu-midas.net/sites/default/files/downloads/MIDAS_recommendations_for_policy_lowres.pdf.

[13] https://www.isa.org.jm/sites/default/files/files/documents/eng9.pdf.

[14] Including anemones, sponges, and corals, as well as octopuses, which have recently been found to lay eggs in sponges attached to nodules.

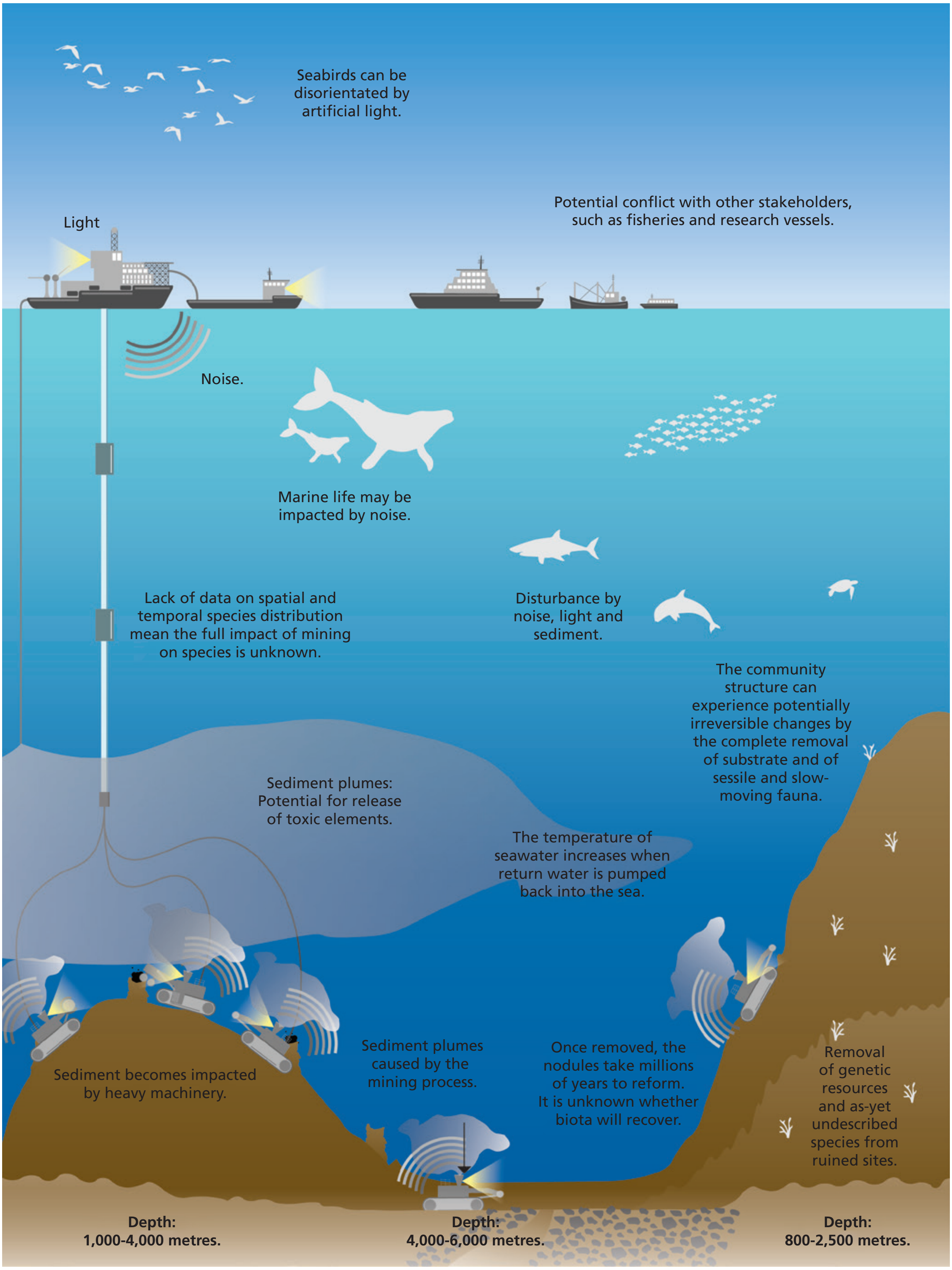



*Figure 5 Primary impact mechanisms of deep-sea mining (UNEP 2022).*

**Box 2 Summary of environment impacts**

Environmental impacts differ between the three main methods of extraction (Weaver and Billett 2019).

**Manganese nodules** occur in deep basins where sediment accumulation can be as low as 1 mm per thousand years. Ecosystems with nodules have great diversity, with some organisms seeming rare. There are insufficient data to understand the dynamics of the ecosystem, and how different species interact. The seabed of the CCZ has no tectonic activity, allowing the sediment nodules to develop over millions of years. The organic flux is low, with less than 1% of primary production at the surface reaching the deep ocean floor. This 'marine snow' is thought to be a primary food source for the fauna in the sediment, attached to the nodules and in the water column. The abyssal plains that host the highest concentrations of nodules consist of soft sediments where the nodules are the only hard substrate that can be used to attach sponges, corals, etc. As a result, 60–70% of megafaunal species use nodules as an attachment point or shelter (Simon-Lledó *et al.* 2019a), and are not found in adjacent areas without nodules.

A nodule collector machine may mine 200–300 $km^2$/year to produce 2–3 Mt of nodules. The collector will scrape the top 10 cm of the seabed (the bioturbated or bioactive layer), sift out the nodules, and discharge the sediment behind. Large particles will settle relatively fast but finer particles may stay in suspension and travel far. The sediment that settles will have low shear strength and cohesion, and may be susceptible to resuspension particularly if meso-scale eddies increase bottom currents (Purkiani *et al.* 2022). The extraction process kills biota and any recolonisation may require the original cohesive state to be re-formed—a process that may be very slow. Owing to the lack of nodules (which form over a million years or more), species dependent on hard surfaces will not return.

The sediment plume from the collector has been modelled in several studies. For every tonne of nodules recovered, 2.5–5.5 tonnes of sediment will be discharged at rates of tens of kilograms per second. The very low background rate of sedimentation renders surviving fauna very susceptible to smothering or blocking of their feeding or respiratory organs.[12] Some models suggest effects may be detected as much as 50–100 km from the mining site (Gillard *et al.* 2019), but recent studies with a pre-prototype collector system in the CCZ suggest that sediment rises up to 10 m above the sea floor and is transported by bottom currents for several kilometres (Muñoz-Royo *et al.* 2022).

Owing to the mining process removing the surface sediment layer and fauna together with the nodules, ecosystem functions will be affected and recolonisation of the disrupted areas extremely slow. Even small-scale benthic (sea bottom) experiments from the 1990s did not show significant recovery after the following three decades. In the 'DISturbance and reCOLonisation experiment' (DISCOL) conducted in 1989, the presence of suspension-feeders remained significantly reduced in disturbed areas after 26 years (Simon-Lledó *et al.* 2019b), with a lower diversity in disturbed areas and markedly distinct faunal compositions along different disturbance levels. Also, microbial activities, biogeochemical processes, and the benthic food web were significantly reduced (Stratmann *et al.* 2018a, b; Vonnahme *et al.* 2020; Haffert *et al.* 2020). Extracting millions of tonnes of nodules requires very large areas to be mined (section 3), giving rise to potentially high and very widespread environmental and ecological impacts.

**Cobalt-rich crusts (CRCs)** occur as layers coating the rocky tops and upper flanks of seamounts, with the most promising deposits occurring between depths of 800 and 2500 m. Seamounts may show more biomass than on adjacent continental margin slopes owing to high densities of structural species such as corals that provide complex habitat, and increased overall productivity. Reflecting the wide range of depths, many different species can be found on a single seamount, of which many are slow-growing, long-lived, and slow to reproduce. Some cold-water corals are known to live for hundreds to thousands of years (see, for example, Schlacher *et al.* 2014), and faunal recovery from the mechanical impacts of mining is likely to be very slow. Indeed, studies of faunal recovery on seamounts off New Zealand following bottom trawling showed few signs of recolonisation after 10 years (Williams *et al.* 2010). Seamounts are globally abundant, yet their ecological significance, heterogeneity, the fragility of their fauna, and poor knowledge of their connectivity and biodiversity have resulted in the UN Food and Agriculture Organization considering the taxa on seamounts to be indicators of 'vulnerable marine ecosystems' subject to special protection from fishing. Some seamounts rise thousands of metres above the seafloor and shape ocean currents, bringing nutrient-rich waters to the surface, where the resulting higher productivity supports diverse communities of marine life, including commercial fisheries. They can also provide food and shelter for marine mammals, sea turtles, and large predators during migrations.

The mining of CRCs will involve grinding or scraping the surface of the seamounts or other topographic features to a depth of up to 25 cm.[13] Assuming a crust thickness of 3–6 cm, Hein *et al.* (2010) estimated that 9–17 $km^2$ will be mined per million tonnes of ore extracted, whereas He *et al.* (2011) estimated that up to 60 $km^2$ would need to be mined per year for the same yield. (Each operator is likely to mine between 1 and 2 Mt of ore per year over a 20-year mining operation.) Given the high productivity of some seamounts with their role in local primary productivity and attracting fish, invertebrates, and marine mammals, some may be much more vulnerable than others to adverse environmental impacts.

**Seafloor massive sulfide (SMS)** bodies are deeper, extending tens of metres into the seabed. As pointed out by Boschen *et al.* (2013), two main communities exist, depending on whether vents are active or not: active vents support the hydrothermal vent specialists, whereas inactive deposits are inhabited by the background fauna. Whether there are additional specialisms responding to the chemical environment of inactive deposits is yet unproven.

Hydrothermal vent specialists are supported by chemosynthetic bacteria reliant on the methane- or sulfide-rich vent fluids for primary production, so that they only grow near active vents. More than 600 new species associated with vents have been described. The unique ecosystems of active vents occur in relatively few locations, so their destruction would have immediate effects on biodiversity. Recovery of assemblages does take place in nature with the stops and starts of vent systems, but may rely on connectivity between populations (Van Dover 2014).

The stability of vent systems may differ between those at rapidly moving mid-ocean ridges and those at slow-moving ridges and subduction zones, with hydrothermal activity ceasing and restarting with a hiatus lasting between less than one and several thousands of years (Jamieson and Gartman 2020). In the former, hydrothermal vent fauna typically have rapid growth rates enabling recolonisation. In the latter, however, the stability (Du Preez and Fisher 2018) can provide the conditions for species to evolve longer lives and slower reproduction rates, with implications for their recovery potential in the event of being destroyed.

The protection of active vent systems in SMS mining is an important issue: some have been designated already as Ecologically or Biologically Significant Marine Areas and protected in national laws (Menini and van Dover 2019); one has even been mooted as a possible World Heritage site, although this site now sits within an ISA exploration contract. Given the diversity of vent systems and their longevity and stability, especially in the Southern Hemisphere, it is argued that there should be a presupposition that active vent systems should be 'off limits' and a minimum boundary set to avoid disturbance (e.g. Johnson 2019).

The fauna colonising inactive deposits has been less well studied but may contain the background fauna also found on seamounts, typically being sessile, filter-feeding, long-lived, and slow-growing (taxa such as sponges, hydroids, corals, anemones, squat lobsters, brittle stars, and sea cucumbers). These take advantage of the hard substrata provided. Once disturbed, any recovery time for background fauna is likely to be on a timescale of decades or longer.

SMS mining can be expected to affect smaller areas of the seabed (owing to the depth of the ore) and may have smaller plumes where the SMS substrate is harder than the soft muds of the nodule-rich areas. On the other hand (GESAMP 2016), the pulverisation of the deposits will produce reactive sulfide mineral surfaces that oxidise to generate acid and release potentially harmful metals (as in acid mine discharges from terrestrial mines). Metals released include heavy metals (see, for example, Fuchida *et al.,* 2019), although the presence of iron in SMS deposits may mitigate their toxic effects (Hu *et al.* 2022), and there is a natural background of discharges containing metals from vents to which the biota may have adapted.

In all three cases, there is the additional discharge of sediments from the surface vessel where the initial slurry is dewatered and sediment removed, and the potential to interfere with any commercial fisheries active in the area concerned. Some proposals are for these discharges to be in mid-depths; others are to return to the seabed to minimise the environmental footprint and avoid affecting mid-water ecosystems. In all cases, the plume may affect organisms by clogging the filter-feeding mechanisms of animals that rely upon clean current flow containing zooplankton and particulate organic material. In addition, deposits from plumes may overwhelm organisms and prevent juveniles from settling, and affect larval dispersal, potentially disrupting species/population connectivities.

the mined area (Box 2). Ouillon *et al.* (2022a; 2022b) examined the fluid dynamics of sediment plumes and noted that variations in turbulence and particle settling velocity produced orders of magnitude differences in the predicted spread from the collector device. Slurries at the seabed may also flow even on a very gradual slope for as far as the slope continues. Recent work *in situ* confirms the importance of processes (turbidity current dynamics) that have been excluded in previous modelling efforts (Muñoz-Royo *et al.* 2022), so that fundamental and applied fluid-mechanics research is needed before models can accurately predict commercial-scale scenarios.

Sediment discharges from the surface processing vessel may be adjustable as to where they take place (Peacock and Ouillon 2023). The preferred option is to release the sediment near the seabed on the area already denuded of life by the mining operation. Finally, there is the possibility of returning the sediment-laden water to the collector vehicle and adding it to the primary collector plume. In each case there is a risk not only of physical impacts but also of toxic effects from any chemicals released from the sediment.

### *4.2.3 Microorganisms in the deep sea*

Microorganisms exploit a wide range of processes in utilising inorganic carbon and scavenging diverse organic compounds involved in the deep-sea carbon cycle (Dick *et al.* 2013; Huang *et al.* 2019; Orcutt *et al.* 2020), and the distinct geochemical environments in active vents have bred special microbial communities that are so different from terrestrial bacteria that the human immune system fails to recognise 80% of them (Gauthier *et al.* 2021). They thus provide a diverse genetic resource with potential for medical and commercial applications. Bacteria in nodule-containing abyssal sediments are an important local source of primary production which can match the biomass available from detritus (Sweetman *et al.* 2019).

Marine sediments in general store almost twice as much carbon as terrestrial soils (Atwood *et al.* 2020) and their disturbance could lead to the carbon being remineralised to carbon dioxide. There is evidence that mining disturbance does affect carbon processing; Stratmann *et al.* (2018a) found that the total system throughput of carbon in areas ploughed 26 years ago in abyssal sediments was 56% lower inside plough tracks compared with areas outside; while microbially mediated biogeochemical functions need more than 50 years to return to undisturbed levels (Vonnahme *et al.* 2020). Ruff *et al.* (2019) found loss of seafloor integrity reduced the efficiency of methane consumption, and that several years were required to restore a methane-consuming microbiome. However, the small quantities of organic matter that reside in deep-sea sediments have been highly processed and are considered unlikely to be remineralised (Orcutt *et al.* 2020). At the current state of knowledge, deep-sea sediment disturbance seems unlikely to lead to significant additional release of carbon dioxide, although uncertainties remain.

The importance of microbiology is recognised in the inclusion of microbial information on '*diversity, abundance, biomass, connectivity, trophic relationships, resilience, ecosystem function, and temporal variability*' in the 2018 draft regulations for exploitation (ISA 2019).

### 4.3 Scope for reducing impacts

Under the Law of the Sea Convention, the ISA has a duty to protect the marine environment from serious harm (Smith *et al.* 2020). Exploitation regulations will include environmental impact assessments, monitoring, and threshold values, while Regional Environmental Management Plans (REMP) aim to protect specific areas. In the CCZ (Figure 6), the ISA has assigned no-mining areas called Areas of Particular Environmental Interest, with the aim of safeguarding biodiversity and ecosystem function (Kaker *et al.* 2017; ISA 2021). Our understanding of the drivers that constrain species distributions and the degree of connectivity between communities is still limited and raises the question whether the fauna in Areas of Particular Environmental Interest would in fact speed up any process of recolonisation in the mined areas. As a result, there are calls (e.g. Vanreusel *et al.* 2016) for more protected areas to be established within each contract area to facilitate recolonisation of impacted seafloor areas.

Beyond the allocation of conservation areas, other approaches to impact reduction would include designing mining tools to minimise sediment disturbance; returning mid-water plumes to the seabed mining location; screening sediments for harmful compounds before return to the seabed; minimising the intensity and frequency of noise and light both at the seabed and at depth; and using the latest mining technology to ensure full resource extraction to minimise the need for re-mining an area (Billett *et al.* 2019).

In terrestrial mining, a four-tier mitigation hierarchy is used to protect biodiversity: firstly, loss avoidance; secondly, minimisation; thirdly, remediation; and, as a last resort, biodiversity offsets (Van Dover *et al.* 2017). Comparing deep-sea mining with this, avoidance of biodiversity loss is not possible because the habitat will be destroyed and biodiversity may also be lost in the water column and areas of the seabed affected

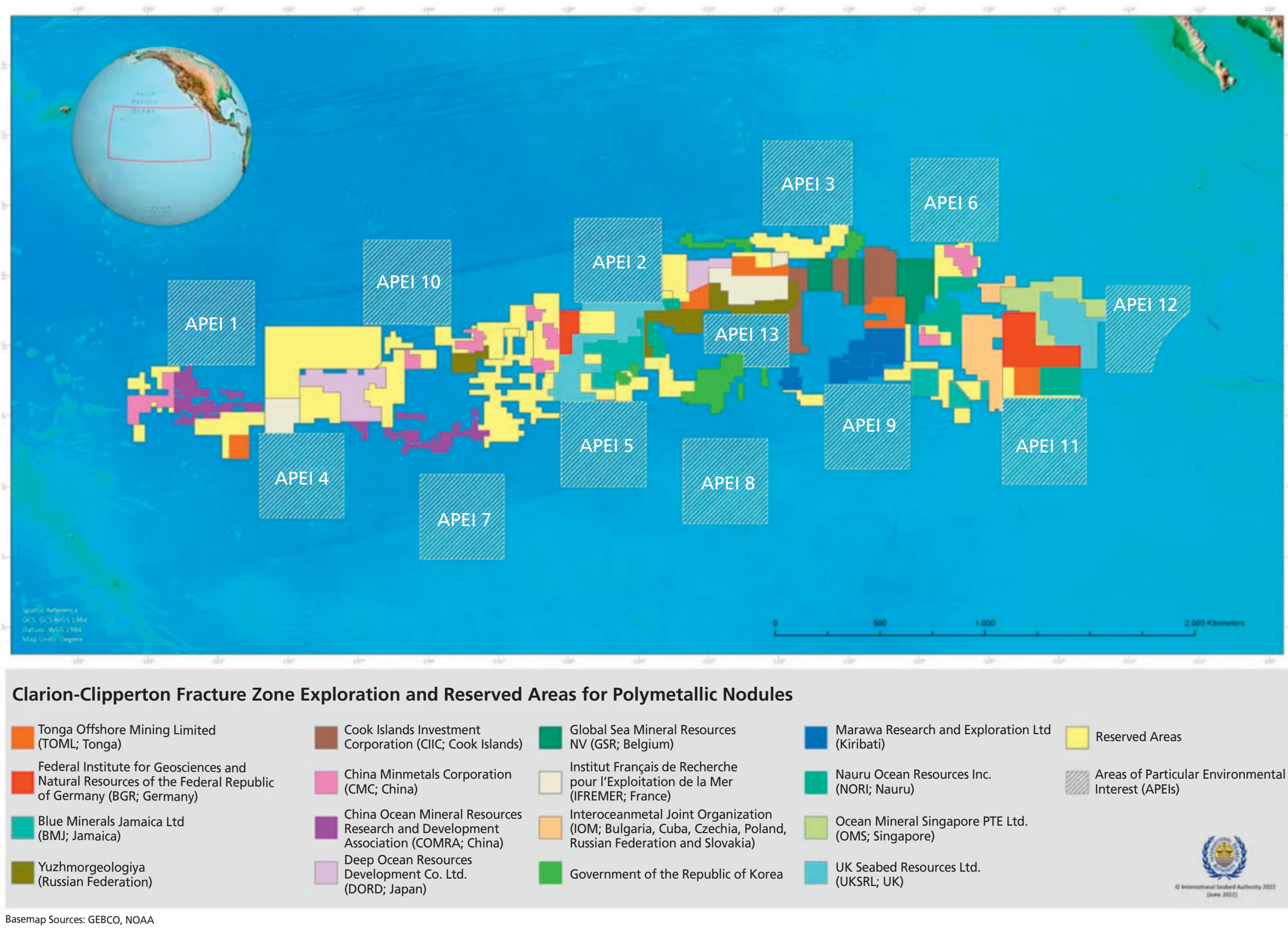



*Figure 6 Map of the CCZ with mining contract areas outlined in colour and the Areas of Particular Environmental Interest or no-mining zones outlined in white. Source: ISA.*

by sediment plumes (Niner *et al.* 2018). Impact minimisation is constrained by the lack of physical boundaries in the marine environment, in contrast to terrestrial mining where engineering design can limit impacts to the mining site.

For plume formation, Weaver *et al.* (2022) note that different mining vehicle designs may generate substantially different plumes, that the degree to which mining vehicles are designed to limit plume impact should be a key criterion in the environmental impact assessment, and that innovation to minimise plume impact be encouraged. This would require the setting of thresholds for sediment burial or fine sediment suspension against which mining vehicle performance can be assessed. Biologically relevant thresholds will need to take into account not only the immediate impacts of particle load and toxicity, but also long-term effects, because mining in the CCZ is expected to continue for 30 or more years. Niner *et al.* (2018) suggest that the use of shrouds on collecting and cutting systems and the development of methods to reduce the creation of fine particulate materials might reduce impacts of plumes, while Gillard *et al.* (2019) suggest plume fallout could be restricted to a smaller area by turbulent discharge to speed up sediment flocculation.

Remediation is an objective of terrestrial management plans, but is likely to be ineffective owing to the slowness of deep-sea recolonisation of disturbed habitats, the large areas affected and the irreversibilily of some habitat loss (e.g. of nodules and corals). Encouraging recolonisation is currently based on the assumption that preserving undisturbed communities may provide larvae to the impacted site. To support this, research is underway on recolonisation using artificial nodules (Gollner *et al.* 2022). Billett *et al.* (2019) argue that speeding the restoration of marine ecosystems along the same principles that are applied on land would require experimental research to be undertaken during the exploration phase and before an environmental impact statement is submitted, and that the feasibility and effectiveness of such measures should be demonstrated before contracts to exploit deep-sea minerals are agreed.

Finally, offsets to compensate for the faunal loss over hundreds of thousands of square kilometres of seabed are impossible on a like-for-like basis. To overcome this, some have suggested compensatory remediation might be offered (e.g. restoring coral reefs in exchange for loss of deep-sea biodiversity); however, because restoring coral reefs is a separate objective irrespective of the presence or absence of mining, this makes no scientific or logical sense. It has also been pointed out that compensating biodiversity loss in international waters with biodiversity gains in national waters could constitute a transfer of wealth that runs counter to the Law of the Sea, where benefits from deep-seabed mining must accrue to the international community at large, as part of the common heritage of humankind.

Unless contractors include ecosystem services and the costs associated with their loss or impairment as part of their decision-taking, and as part of an ethical approach to ensuring the health of the oceans for the common heritage, motivations to devise technical solutions to reduce environmental harm may be lacking. At present, there is little economic incentive for driving engineering innovations to minimise impacts, because many of the ecosystem functions provided by deep-sea biodiversity (e.g. regulatory services of carbon sequestration and nutrient cycling, provisioning services such as potential contributions from bioprospecting, and cultural services) are free goods whose loss is unrecognised by the cost–benefit analyses of whether or how to mine. At present, there is no burden of proof on the applicant to show that their activities will not harm the environment, and regulation is the main tool to determine the level of 'acceptable' biodiversity loss in the deep sea. Any process to make more holistic assessments of risks and benefits requires public, transparent, and well-informed consideration, as well as agreement between the special interests engaged in mining and the global community that represents the common heritage of humankind.

All exploitation proposals require an environmental impact assessment and there is much debate about the adequacy and practicality of conducting such assessments in deep-sea environments. Ideally, after an initial 'desk-top' scoping study, field-based environmental or baseline surveys should be conducted as part of the exploration phase, and an ecological risk assessment performed to assess the potential severity of impacts and identify mitigation strategies. However, although environmental impact assessments for terrestrial mining have a well-developed methodology, deep-sea practice is still under development and subject to criticisms related to its inadequate baseline data, insufficient detail of the mining operation, insufficient synthesis of data and the ecosystem approach, poor assessment and consideration of uncertainty, inadequate assessment of indirect impacts, inadequate treatment of cumulative impacts, insufficient risk assessment, and lack of consideration of linkages with other management plans (Clark *et al.* 2020).

## 5 Policy implications

Issues that European policy-makers must address can be separated into those within the EU's sphere of competence and those with a more global dimension, where the EU's role would be through interventions in international agreements and conventions. The former relates to the demand for the metals in the EU's green transition (section 5.1), while the issues explored in sections 5.2–5.6 are more in the form of questions to raise in diplomacy, in ISA management meetings and conventions such as the Convention on Biological Diversity and the United Nations Convention on the Law of the Sea (UNCLOS), and in the development of the recent BBNJ Agreement.

### 5.1 The need for deep-sea mining

Section 2 discussed the supply and demand for the metals expected to be extracted by deep-sea mining. Haugan *et al.* (2019) have pointed out that the industry is continually developing solutions that can use cheaper and more abundant resources to avoid costly metals. Alternative energy technologies are already under investigation that change demand for specific metals. New solid-state battery designs avoid the use of cobalt and nickel and have great durability and longevity. Moreover, deep-sea resources could provide only some of the critical materials required for current electric-vehicle batteries (lithium and graphite are also expected to be in short supply). This perspective argues that seabed minerals are not needed (Teske *et al.* 2016; Månberger and Stenqvist 2018); nor could they supply any gap in nickel or cobalt demand before the 2030s because of the need to set up the transport and processing chains. Rather, sustainable development should prioritise reducing human demands on planetary resources that are already exceeding sustainable rates of harvesting and exceeding planetary boundaries, and accelerate moves towards circularity. The uncertainties about the scale of future demand make it difficult to justify the rush to develop the mining code currently underway as a result of the 2-year rule. Such concerns are also expressed when doubts over the scale of need are weighed against environmental impacts (e.g. Heffernan 2019; Miller *et al.* 2021).

On this perspective, the pressure for mining is driven by industry and economic interests rather than demands from the transition to a green economy. For instance, venture businesses seek new business opportunities; some nation states may seek new sources of revenue or markets to replace declining industries based on fossil fuels; technology developers may seek new markets and sources of public funding for assets and expertise in danger of becoming stranded as their fossil-fuel-driven business declines.

Recycling is critical to mitigating demand for virgin materials, but efficient systems are complex and involve multiple actors whose objectives may not be aligned, requiring a regulatory system to overcome barriers (Hagelüken and Goldmann 2022). Ideally, all stakeholders (from manufacturers to recyclers) should be incentivised to retain a material's value throughout the raw material to end-of-life stages. The regulatory framework should provide incentives and duties in product design for recyclability, and in collection and disassembly networks, so that chemical and metallurgical specialist businesses can apply the necessary recycling technology (Cimprich *et al.* 2022; Hool *et al.* 2022). Extended producer responsibility should be based on the entire product design, product, consumer, end-of-life treatment, and handling chain to ensure that all actors' interests are aligned towards more circularity and efficient recycling (Hagelüken and Goldmann 2022).

Although larger quantities of used electric-vehicle batteries will only be available towards the end of this decade, it is necessary to start developing business models and setting up the corresponding take-back, repair, and recycling structures now. The European Commission's latest initiative is thus to be welcomed and should be just the first step in establishing a framework that encourages recycling for all renewable energy systems.

### 5.2 Assessing the environmental impacts of deep-sea mining

Major knowledge gaps remain about deep-sea ecosystem structure and function, the species present, how they interact, and their tolerances and resilience. Even so, on the basis of existing information it is clear that mining will have the following effects:

- Biota in the areas directly mined at the seabed will be killed.
- The remaining sediment discarded on site is likely to be inhospitable to recovery in decades to centuries for nodule and CRC mining and decades for SMS.
- Loss in hard substrates and in the structure of habitats (e.g. loss of nodules or corals) may lead to indefinite reductions in biodiversity.
- The collateral ecological damage through sediment plumes may expand the area of impact at the seabed and in the water column.
- Noise, vibration, and light are other factors that may affect biota at the mining site, and it remains unclear to what extent mining disturbance may disrupt the microbiological processes determining emissions of carbon dioxide and methane.

Such impacts may extend to hundreds of thousands, potentially millions, of square kilometres if mining approaches its planned scale to recover hundreds of millions of tonnes of ore from nodules. The scale and nature of this has persuaded an increasing number of nation states and regional groups such as the European Union to call for a moratorium on deep-sea mining until ecological impacts are better understood and mitigation strategies developed.

The ISA is charged with managing the deep-sea resources in 'the Area' '*for the benefit of [hu]mankind as a whole … taking into consideration in particular the interests and needs of developing states*', while ensuring '*effective protection for the marine environment from harmful effects of seabed mining activities*' (UNCLOS, Article 145) The risk of '*serious harm*' also features in the Convention as a threshold for an application to be denied. For exploration, the ISA has defined serious harm as representing '*a significant adverse change in the marine environment determined according to the rules, regulations and procedures adopted by the Authority, on the basis of Internationally Recognized Standards and Practices*', but is still debating what environmental criteria will apply for exploitation contracts as part of its strategic plan for 2019–2023 (ISA 2018) to '*satisfy the extensive marine environmental protection requirements of the Convention, as well as take into account relevant aspects of the Sustainable Development Goals and other international environmental targets, such as the Aichi Biodiversity Targets*'.

It is not yet established what level of environmental harm would be regarded as serious or significant enough to justify refusal of a contract (or ultimately as grounds for compensation). From a scientific perspective, Levin *et al.* (2016) discussed these terms and stressed that impacts need to be considered in the context of their spatial and temporal extent; for instance, some resources are in isolated habitats (vents or seamounts) with high endemism so that mining may break connectivity between local ecosystems and risk local extinctions. Additional factors include the duration, frequency, and intensity or magnitude of operations as well as the number of mining contracts in a region. In addition, deep-sea biota tend to have long lifetimes, slow growth, and late maturity, reducing resilience to and recovery from disturbance, with some unlikely or extremely slow to recover at all. This raises many issues on indicators, data requirements, and on setting thresholds that would allow 'serious or significant' to be determined (Box 3).

Environmental goals and objectives (such as those included in other conventions, for example the Convention on Biological Diversity) would underpin regulations sufficiently rigorous to withstand legal challenges, and lead to the standards for monitoring, modelling, data handling and analysis that would allow thresholds above which 'serious harm' occurs to be determined. Tunnicliffe *et al.* (2020) offer illustrative examples of a strategic goal and specific objectives, as shown in Table 2.

Currently such overarching goals and objectives have not been established and the draft standards and guidelines developed by the ISA's Legal and Technical Commission lack threshold values for the protection of

**Table 2 Candidates for strategic goals and objectives for ISA (Tunnicliffe *et al.* 2020)**

| Overarching strategic goal |
|---|
| 'To sustain marine (benthic and pelagic) ecosystem integrity including the physical, chemical, geological and biological environment'. |
| **Possible specific objectives** |
| • Protect ecosystems from contamination by pollutants generated during any phase of the mining process.<br>• Maintain the ability of populations to replace themselves, including ensuring population connectivity and the preservation of suitable habitat.<br>• Prevent the degradation of ecosystem functions (e.g. the long-term natural productivity of habitats, elemental cycling, trophic relationships).<br>• Prevent significant loss of genetic diversity, species richness, habitat or community types, and structural complexity on a long-term basis.<br>• Sustain ecosystem services (e.g. carbon sequestration) recognising that many are yet to be discovered.<br>• Maintain resilience to prevent regime shift, and to support recovery from cumulative impacts, including mining, that can affect source populations and communities, connectivity corridors, life-history patterns, and species distributions. |

the marine environment, making it difficult to assess the seriousness of environmental impacts, compare the efficiency of collector designs, and inform other decisions. This weakness has been recognised by some Member States (see, for example, ISA 2022b) who have proposed that quantitative environmental thresholds should be established to protect the marine environment, and measurable thresholds should be in place before applications for exploitation are considered. Initial thresholds proposed cover toxicity, sedimentation rates, turbidity, light, and noise, as a result of which the ISA is establishing three technical subgroups to consider standards for toxicity, turbidity/resettled sedimentation, and for noise and light. However, as noted in Box 3, there is a much wider range of possible threshold variables including fundamental biological thresholds related to biodiversity.

Levin *et al.* (2016) suggest that a multi-dimensional, scientific approach is needed to set thresholds, involving expert panels to establish criteria for environmental impact assessments. Specific mining projects should have to complete such assessments and these should be assessed against criteria for serious harm before contracts are evaluated. Such measures could well place demands on expertise not currently available within the ISA, which currently relies on *ad hoc* subgroups dependent on voluntary participation by external experts, so that further integration of environmental criteria into the evaluation process could require more formal sources to be set up. Pew (2023) sees options as including the establishment of an environmentally focused advisory commission within the ISA, or links with outside bodies such as GESAMP. Another possibility would be to establish relationships with developing expertise in the BBNJ.

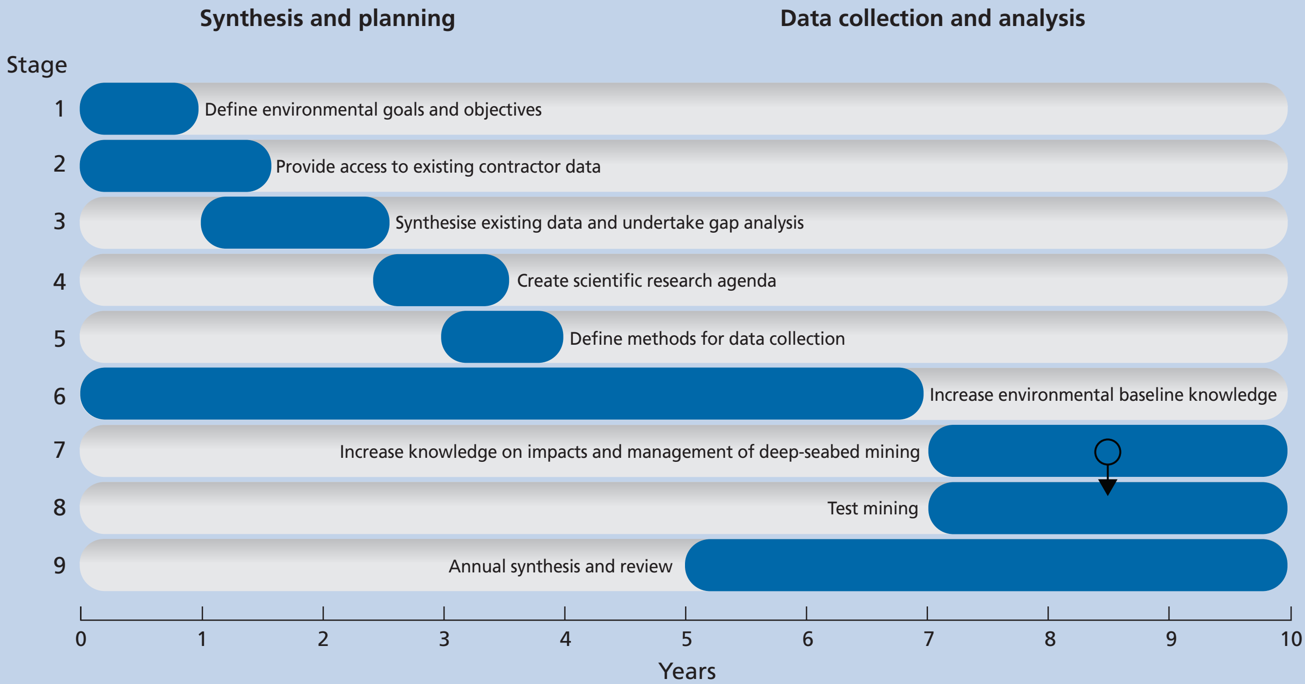
Some areas such as active vents have such unique biological characteristics that they have been proposed to be out of limits to mining (Van Dover *et al.* 2017), especially because current regulations place no prohibition on mining at active hydrothermal vents. Orcutt *et al.* (2020) also argue that active vent systems should not be mined in order to preserve microbial ecosystem services for the common benefit of humankind, while van der Most *et al.* (2023) find that vent sites studied in the Indian Ocean meet all criteria for the Food and Agriculture Organization's 'Vulnerable Marine Ecosystems', the International Maritime Organization's 'Particular Sensitive Sea Areas', and the Convention on Biological Diversity's 'Ecologically or Biologically Significant Areas'. The ISA has recognised in its exploration regulations (e.g. Nodules Exploration Regulation 31(4)) that serious harmful effects on vents and other vulnerable marine ecosystems should be

**Box 3 Indicators, data requirements, and thresholds related to assessing harm to the marine environment**

Possible indicators that could allow a judgement on the degree of harm include the following:
- Biodiversity (species richness, species extinction, evenness, phylogenetic distinctness, rarity, endemicity, abundance, genetic structure).
- Community structure, key ecosystem components.
- Changes to habitat structure and function.
- Risk to endangered species.
- Basic characteristics of the ecosystems: biomass, primary productivity, heterogeneity, connectivity, respiration, nutrient cycling, carbon cycling.
- Resilience and recovery potential.

In turn, this would require scientific knowledge on the following:
- Regional distribution of habitats (active and inactive vents, seamounts, other features).
- Natural variability, connectivity, succession endemicity of taxa.
- Ecotoxicology of plumes.
- Interactions with fish and fisheries (seamounts).
- Faunal sensitivity to changes in substrate and chemistry.
- Impacts within the water column and at the surface.

Amon *et al.* (2022) concluded that, despite recent research, there was insufficient knowledge to allow evidence-based assessments whether mining operations would cause "serious harm'. Providing such data would require a research agenda designed to meet internationally agreed environmental goals and objectives, as in the roadmap in Box 3 Figure 1. Recommendations for baseline measurements and monitoring of mining impacts have also been suggested by Durden *et al.* (2018), including the role of microorganisms.




*Box 3 Figure 1 Roadmap for closing key scientific gaps (Amon et al. 2022).*

avoided; however, the necessary procedures to apply this have not been established.

Protecting active vents from mining impacts is included in Regional Environmental Management Plans (section 5.6), but Blanchard and Gollner (2022) conclude that current management measures need further work to recognise the ecological attributes of ecosystems and their connectivity. A particular challenge is that in most cases where mineral exploration is expected to occur, the main areas of interest are in fields that remain active (Jamieson and Gartman 2020), and that currently inactive vents may reactivate.

### 5.3 Marine biodiversity, the 'common heritage' of humankind, and other conventions

As pointed out by Jaeckel (2020), when the Law of the Sea Convention was negotiated, significant components of deep-sea biodiversity were unknown (including the chemosynthetic ecosystems); rather, the ISA's mission was seen as that of sharing the economic benefits to be extracted from almost lifeless deep-sea sediments. We now know that deep-sea biodiversity is rich and that its loss may be unavoidable (Niner *et al.* 2018; Levin *et al.* 2020) owing to the vulnerable nature of the environments to mining impacts, the limited technological capacity to minimise harm, and the limited and slow recovery potential of deep-sea ecosystems. At the same time, international priorities since 1994 have addressed the protection and reversal of biodiversity loss. Protection of ocean biodiversity is included in the Convention on Biological Diversity, and is a central theme of the BBNJ Agreement to address biodiversity and sustainable use in areas beyond national jurisdiction (Tladi 2014; https://www.un.org/bbnj/). In these conventions it is recognised that biodiversity underpins ecosystems services such as carbon regulation or the provision of possible future pharmaceuticals, and is part of the common interest of humankind.

Some authors (e.g. Kim 2017) have pointed out that, while decisions on mining have multiple dimensions (economic, environmental, and ethical), the ISA's mission is primarily seen as facilitating resource development. Pressures thus exist for the ISA to evolve from a 'resource management' model to one that is more in line with the increasing focus on biodiversity and environmental protection. In this context, COP15 of the Convention on Biological Diversity established a target to preserve 30% of ocean areas by 2030, and the new BBNJ Agreement is established *inter alia* to protect marine biodiversity in the Area. Even though these later legal agreements do not directly impinge on the competence of the ISA, they are hardly consistent with the large-scale loss of biodiversity likely to occur if substantial parts of the currently intact deep ocean are mined. Further thought may be required if direct conflicts are to be avoided between the objectives and missions of these conventions.

The Law of the Sea Convention stated that the mineral resources of the Area were the common heritage of humankind, and that ISA should manage those resources on behalf of humankind as a whole. This has raised questions as to the degree to which ISA discharges this mission and led to calls for greater public participation and transparency (Ardron *et al.* 2023; Bosco *et al.* 2023). Some reviewers (e.g. Jaeckel *et al.* 2017; Niner *et al.* 2018) have suggested that potential conflicts could be addressed if the ISA were to develop the regulatory capacity to ensure effective protection of the marine environment from harmful effects of mining in a transparent and inclusive manner. This would include the creation of environmental consents, evidence, inspectorate and enforcement functions, and would involve a slower process of transitioning from exploration to exploitation. It would also allow the establishment of an international research agenda to fill identified gaps in knowledge required for decision-making and environmental management, before any deep-sea mining takes place.

Furthermore, any deep-sea mining should be approached in a precautionary and stepwise manner; each step should be subject to explicit environmental management goals, monitoring protocols, and binding standards to prevent serious environmental harm and minimise loss of biodiversity. An improved understanding of environmental impacts should ultimately lead to a duty on the ISA to properly assess whether any economic benefits of mining that accrue to humankind are justified by the high risk and the long-term nature of the harm to the environment and its ecosystem services, through an international consensus. The Antarctic Treaty could offer one model whereby nations have agreed to prohibit industrial activity to safeguard it as the common heritage of humankind.

### 5.4 The narrative for public discourse

Some companies have already adopted the public posture that they will not accept metals taken from the deep sea on sustainability and ethical grounds. In a similar vein, the United Nations Environment Programme (UNEP 2022) observed that, once started, deep-sea mining is likely to be impossible to stop; and, once lost, deep-sea biodiversity will be impossible to restore. Since no robust, precautionary approach exists to safeguard the ocean against the potential ecological impacts of deep-sea mining, UNEP concluded that financing of deep-sea mining activities cannot be viewed as consistent with the Sustainable Blue Economy Finance Principles, or compatible with the spirit and intent of the Sustainable Blue Economy.

To counter such conclusions, the industry often claims that the new sources of metals from the deep sea are essential for the green economy. As we noted in section 2.1, there are several reasons why this is contestible. Moreover, some targets for mining (SMS) lack the metals currently seen as critical to the green economy and are driven by elements such as gold. Childs (2019) also found that industry seeks to reduce negative environmental perceptions through communicating a mine's impact in comparison with natural events such as volcanic eruptions or vent shutdown and reformation, thus implying a level of resilience that is not supported by ecological studies.

The narrative on deep-sea mining may also point to the visible environmental and human impacts of terrestrial mining, so that the largely invisible impacts may be cast as the lesser of two evils and out of sight. Such arguments ignore the huge spatial and functional differences between the areas required for terrestrial and marine mining; also that collection of the ore is only the first stage of a supply chain where transport hubs and ore processing and refining will take place on land. As was pointed out in section 4.4, terrestrial mining is subject to mitigation and compensatory measures that cannot be applied in the deep sea, and further opportunities to reduce environmental and human impacts are available to governments by improving governance and enforcement in terrestrial mines.

### 5.5 Regional Environmental Management Plans and marine biodiversity

Regional Environmental Management Plans (REMPs) aim to protect the marine environment from harmful effects across the whole areas affected by mining activities, and are an integral part of the ISA's work on environment protection. As pointed out by Christiansen *et al.* (2022), REMP development is relevant to the effective conservation and management of marine biodiversity in areas beyond national jurisdiction that will be developed in the BBNJ Agreement of 3 March 2023.

REMPs pose huge data challenges. For instance, the draft REMP for the Mid-Atlantic Ridge sulfide deposits (ISA 2022c) identified data needs for the types and distribution of habitats and their representativity at the regional scale; patterns of connectivity between populations of species important for maintaining ecosystem function and processes; mapping corridors of migratory species such as marine mammals and turtles; and identifying feeding and breeding grounds for key species such as marine mammals and large nekton.

This draft REMP includes 'Areas in Need of Protection', which are large-scale areas of ecological importance due to their uniqueness and/or biodiversity. In addition, 'Sites in Need of Protection' are more localised and vulnerable sites that should be protected—typified by active vent sites. Dunn *et al*. (2018) offered a means of identifying such sensitive areas on the basis of marine-reserve design principles. Developing REMPs involves workshops that engage external experts to develop draft plans which are then considered by the ISA in its decision on the final content of the REMP. A Marine Protected Areas Guide has been published to steer the development of guidelines and standards (Grorud-Colvert *et al.* 2021); however, the increasing need for environmental impact assessment is challenging for the ISA in view of the limited in-house environmental expertise, as mentioned in section 5.2.

### 5.6 Mining in national exclusive economic zones

As pointed out by Petersen *et al.* (2016), the distribution of mineral resources varies with the type. Of the 38 million km$^2$ estimated for manganese nodules, only 19% are in a country's EEZ; for the 1.7 million km$^2$ of CRC, 54% are in an EEZ; and for the 3.2 million km$^2$ of SMS, 42% are located in a nation's EEZ.

Some coastal nations typified by Norway are proceeding to evaluate mining in their own EEZ. However, as noted in Box 1, it is not yet clear what technologies would be used; what conditions might be applied to contracts; the objectives, criteria; and methods to be included in environmental impact assessments; nor what mitigation measures might be required. There is an obligation that any national standards should not be less than those applied internationally, although as shown above these are yet to be finalised. Early actions by individual countries could provide valuable data on how to protect the marine environment. Any actions should thus be transparent, and countries encouraged to share data and experience generated with the international community and the ISA. In the case of Norway and other SMS mining plans, while the areas impacted by SMS are likely to be smaller than for CRC or collection of nodules, acid generation and release of toxic metals may be more likely. Transboundary impacts for both adjacent EEZs and the high seas need to be assessed and monitored in transparent and internationally agreed procedures.

### 5.7 A final word

The issue of whether to proceed with deep-sea mining is coming to critical decision points at global and national levels. Supporters argue that additional sources of metals are required to support the energy transition, that deep-sea resources are technologically and economically viable, and that the international regulatory regime should act swiftly to establish rules that allow mining to proceed from the exploratory to exploitation phase. Opponents question the need for deep-sea resources and the urgency of current proposals, and assert that sufficient knowledge is lacking to properly assess environmental impacts and to comply with the requirement to effectively protect the marine environment from harmful effects of seabed mining activities. As policy-makers are being asked to make decisions with potentially long-lasting repercussions, we hope this overview of the scientific aspects of deep-sea mining will help to inform policy decisions both within Europe and worldwide.

## Abbreviations

| | |
|---|---|
| BBNJ | Marine Biodiversity Beyond areas of National Jurisdiction |
| CCZ | Clarion-Clipperton Zone |
| CRC | Cobalt-rich crusts |
| EASAC | European Academies' Science Advisory Council |
| EC | European Commission |
| EEZ | Exclusive economic zone |
| EU | European Union |
| GESAMP | Group of Experts on the Scientific Aspects of Marine Pollution |
| ISA | International Seabed Authority |
| Mt | Million tonnes |
| REMP | Regional Environmental Management Plan |
| SMS | Seafloor massive sulfide |
| UNCLOS | United Nations Convention on the Law of the Sea |

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# DEEP-SEA MINING

## BALANCING NEEDS AND ENVIRONMENTAL DAMAGE

**40% - 77%** **of Europe's clean energy metal needs by 2050 could be covered by recycling.**

**3** of the main metals targeted in deep-sea mining (manganese, copper and nickel) are considered to be of **low supply risk** while cobalt is moderate.

Globally, as much cobalt is lost every year as is needed to equip up to **3 million** electric cars.

The current trajectory of efficiency gains in metal intensity through innovation means that **terrestrial mineral reserves will be sufficient** to meet the renewable technologies demand to realise 2050 Paris Agreement targets.

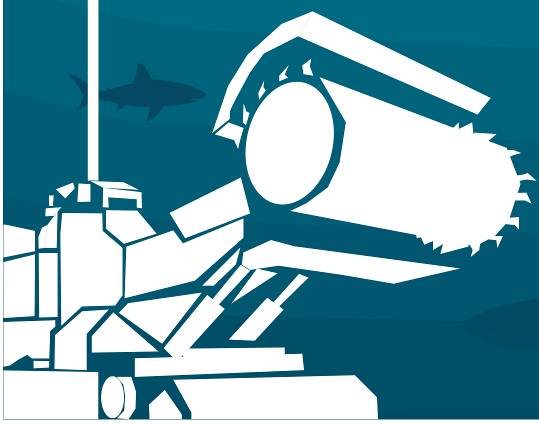
**Terrestrial mining requires a small fraction of areas** compared to those needed at the seabed and has a 4-stage mitigation hierarchy that cannot be applied at the deep sea.

**The extraction process kills all life**

**60 - 70%** of megafaunal species use nodules as an attachment point or shelter.

Nodules take **MILLIONS OF YEARS** to reform.

The deep sea is characterised by high biodiversity, thousands of rare and highly adapted species, unique habitats, vulnerable ecosystems, low metabolic rates and long life.



**A 16-metre-wide robot** gathering 400 tonnes of nodules per hour removes **100,000 tonnes from 10,000 km²** of seabed over 25 to 30 years, creating irreparable ecological damage.

# EASAC

EASAC – the European Academies' Science Advisory Council – is formed by the national science academies of the EU Member States to enable them to collaborate with each other in giving advice to European policy-makers. It thus provides a means for the collective voice of European science to be heard. EASAC was founded in 2001 at the Royal Swedish Academy of Sciences.

Its mission reflects the view of academies that science is central to many aspects of modern life and that an appreciation of the scientific dimension is a pre-requisite to wise policy-making. This view already underpins the work of many academies at national level. With the growing importance of the European Union as an arena for policy, academies recognise that the scope of their advisory functions needs to extend beyond the national to cover also the European level. Here it is often the case that a trans-European grouping can be more effective than a body from a single country. The academies of Europe have therefore formed EASAC so that they can speak with a common voice with the goal of building science into policy at EU level.

Through EASAC, the academies work together to provide independent, expert, evidence-based advice about the scientific aspects of public policy to those who make or influence policy within the European institutions. Drawing on the memberships and networks of the academies, EASAC accesses the best of European science in carrying out its work. Its views are vigorously independent of commercial or political bias, and it is open and transparent in its processes. EASAC aims to deliver advice that is comprehensible, relevant and timely.

EASAC covers all scientific and technical disciplines, and its experts are drawn from all the countries of the European Union, plus Norway, Switzerland and the United Kingdom. It is funded by the member academies. The expert members of EASAC's working groups give their time free of charge. EASAC has no commercial or business sponsors.

EASAC's activities include substantive studies of the scientific aspects of policy issues, reviews and advice about specific policy documents, workshops aimed at identifying current scientific thinking about major policy issues or at briefing policy-makers, and short, timely statements on topical subjects.

The EASAC Council has 30 individual members—highly experienced scientists nominated one each by the national science academies of EU Member States, by the Academia Europaea and by ALLEA. The national science academies of Norway, Switzerland and the United Kingdom are also represented. The Council is supported by a professional Secretariat that is temporarily shared between its member academies and by a Brussels Office at the Royal Academies for Science and the Arts of Belgium. The Council agrees the initiation of projects, appoints members of working groups, reviews drafts and approves reports for publication.

To find out more about EASAC, visit the website – www.easac.eu – or contact the EASAC Secretariat at secretariat@easac.eu

EASAC, the European Academies' Science Advisory Council, consists of representatives of the following European national academies and academic bodies who have issued this report:

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**The Royal Academies for Science and the Arts of Belgium**
**The Bulgarian Academy of Sciences**
**The Croatian Academy of Sciences and Arts**
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