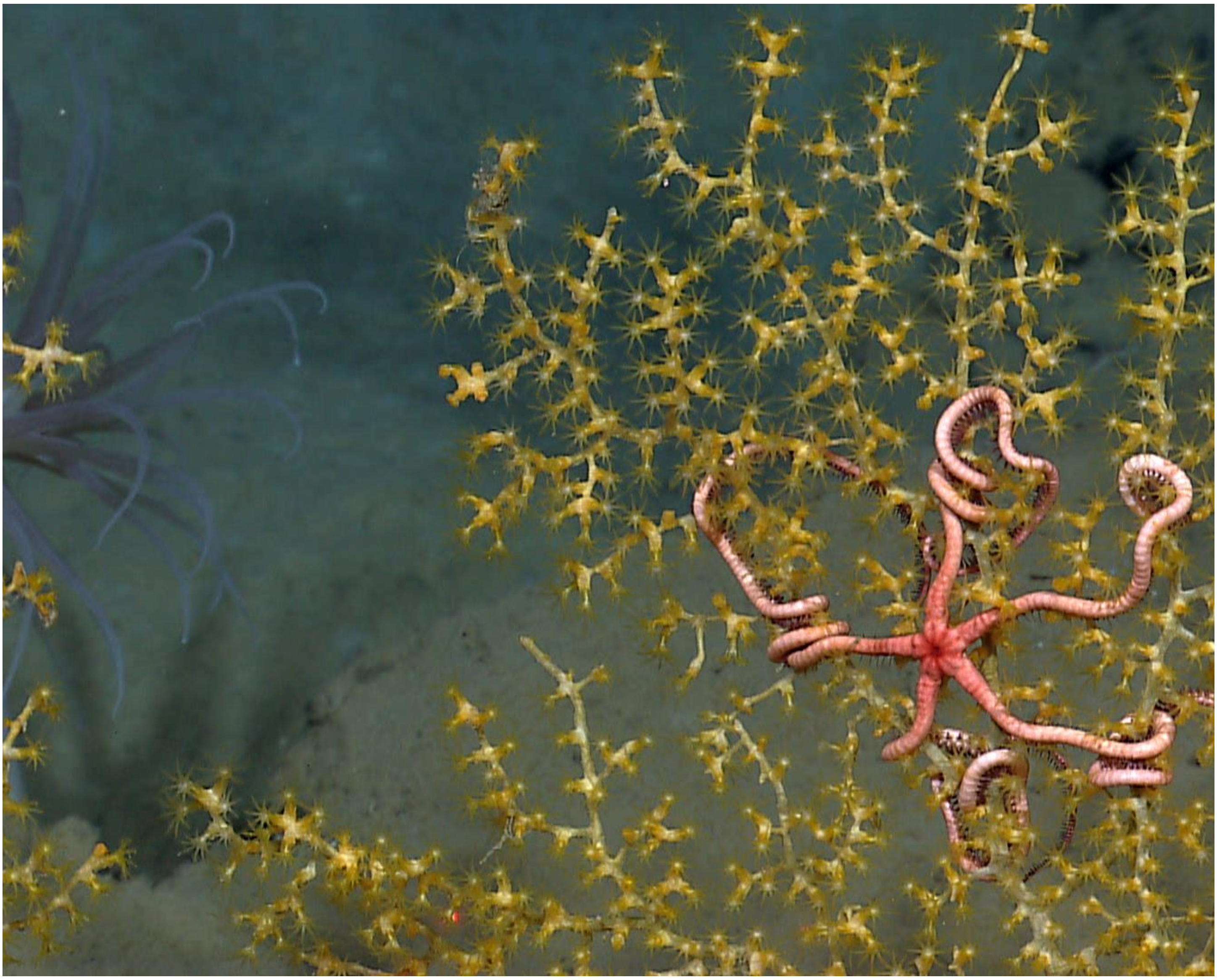
| REPORT



NOAA Office of Ocean Exploration and Research

Update to 'An assessment of the risks and impacts of seabed mining on marine ecosystems'

We now know more, but still not enough to rush into deep sea mining

Authors: Nicky Jenner, Sophie Benbow, Catherine Weller, Pippa Howard

Fauna & Flora protects threatened species and ecosystems worldwide, choosing solutions that are sustainable, based on sound science and take account of human needs. Founded in 1903, Fauna & Flora is the world's longest established international conservation body and a registered charity. For more information see: www.fauna-flora.org

Citation: Fauna & Flora. 2023. Update to 'An assessment of the risks and impacts of seabed mining on marine ecosystems' Cambridge UK. Available from: www.fauna-flora.org

Contents

INTRODUCTION

In early 2020, Fauna & Flora published '*An assessment of the risks and impacts of seabed mining on marine ecosystems'* and raised its concerns about the threat deep-seabed mining (DSM) posed to biodiversity, ecosystem function and dependent planetary systems. DSM has become an increasingly important geo-political issue, connected to a number of intergovernmental processes. It is often portrayed as an exciting new economic frontier for the 'blue economy', which seeks to realise the full economic potential of the ocean and for meeting rising demand for raw materials used in high-tech industries including electronics and battery storage, however, serious reservations remain about the damage it would cause.

Since the release of Fauna & Flora's assessment the timeline for DSM to transition from exploration to commercial exploitation has been accelerated. In 2023 the International Seabed Authority (ISA), responsible for regulating mining in areas beyond national jurisdiction (known as the Area), is being pushed to finalise its exploitation regulations with the first exploitation application for polymetallic nodule mining in the Pacific to follow thereafter.

During the same period, the global community has committed to the conservation and sustainable management of the ocean as reflected in the 2022 Kunming-Montreal Global Biodiversity Framework, whilst there has been growing inclusion of the ocean in climate discussions related to the United Nations Framework Convention on Climate Change (UNFCCC). A United Nations (UN) agreement on the conservation and sustainable use of marine biodiversity in areas beyond national jurisdiction was also finalised in March 2023.[1,i]

In light of the imminent threat posed by DSM for the deep sea, scientific attention on deep-sea environments, the functions and services they provide for humanity, and the potential implications of DSM for life in the deep ocean has increased rapidly with many new studies published.[2] Fauna & Flora has reviewed new evidence emerging since 2020 through 2022 to provide an update to its original assessment report. In this three-year period the number of publications relating to DSM has increased by almost a third, compared to the previous period.

In reviewing the latest evidence, Fauna & Flora focused on research and reviews relevant to the original assessment themes but restricted to the three deep-sea ecosystems with metallic occurrences for which the ISA has issued contracts for exploration: polymetallic ferromanganese nodules on abyssal plains, cobalt-rich ferromanganese crusts, and polymetallic sulphides from hydrothermal vents, with hydrothermally inactive and extinct polymetallic sulphides the most likely to be mined. The update does not cover developments relating to shallow water seabed mining (at depths <200 metres), the mining of marine phosphates nor other deposits subject to mining activity within national jurisdictions.

A number of important systematic evidence reviews have been undertaken by leading deep-sea experts since the release of Fauna & Flora's 2020 report. These provide a detailed assessment of the current state of knowledge relating to the deep sea, risks and impacts of DSM, and the gaps that need to be addressed. The summary presented here is thus not intended to be a comprehensive review of evidence but to showcase areas in which new evidence and analyses shed light on key aspects of the deep-sea environment, risks posed by DSM and options for mitigation, and the extent to which the conclusions of Fauna & Flora's 2020 report are upheld. All these points have implications for decision-making.

[i] https://www.un.org/bbnj/

A RAPIDLY MOVING AGENDA AND IMMINENT DEADLINE

The ISA regulates seabed mining in areas beyond national jurisdiction, with a responsibility to protect the marine environment from serious harm. The ISA has adopted regulations on prospecting and exploration for polymetallic nodules, cobalt-rich ferromanganese crusts and polymetallic sulphides along with recommendations and guidance for contractors. Draft exploitation regulations, standards and guidelines are under development. In June 2021, the Republic of Nauru notified the ISA of its intention to sponsor an exploitation application for polymetallic nodule mining in the Pacific. In doing so, Nauru triggered a *'two-year rule'* – a legal provision which gives the ISA two years to adopt its first set of exploitation regulations for DSM.

Despite ISA member states' efforts to complete these complex regulations by July 2023, it now looks almost certain that deadline will not be achieved. Further, a growing number of ISA member states are pushing against this pressure, and are calling for more time to develop robust and science-based regulations, before any contract for mining can be issued. These regulations not only affect applications to mine the deep seabed in international waters but are relevant within exclusive economic zones too as the UN Convention on the Law of the Sea (Part XII, Article 208), specifies that environmental protections for seabed mining within national jurisdictions should be 'no less effective' than those developed by the ISA.[3] It remains to be seen how the ISA would navigate, in the absence of an agreed regulatory framework, any application submitted for a contract for exploitation. At least one application is expected in the second half of 2023.[ii]

As of January 2023, the ISA has entered into a total of 31 contracts for exploration (which happens before exploitation)**.** Each contract is for a period of 15-years and collectively encompasses a total area of ~1.51 million km^2.[iii] Of these, 19 licenses (each covering 75,000 km^2) are for exploration for polymetallic nodules, the majority (17) in the Clarion-Clipperton Fracture Zone (CCZ) in the eastern Pacific Ocean. Seven contracts each covering an area of 10,000km^2 have been entered into for exploration for polymetallic sulphides. Polymetallic sulphide deposits are located at and near deep-sea hydrothermal vents with three contracts issued in the northern Mid-Atlantic Ridge and four in the Indian Ocean. A further five exploration contracts, each covering 3,000km^2, have been issued for cobalt-rich crusts (associated with seamounts) in the Western Pacific Ocean. 22 countries are sponsoring contracts for exploration in the Area.[4] DSM-related activities are also underway within a number of national jurisdictions.

Lack of basic knowledge about the deep sea and the risks and impacts of DSM has raised widespread concern whilst the accelerated timeline and rapidly moving agenda has led to bifurcation of opinion towards a precautionary position. In September 2021, a motion calling for a moratorium on deep-seabed mining was adopted with overwhelming support by the IUCN World Conservation Congress, including support from 81 governments and government agencies.[iv]

In 2022, the President of Palau launched a new regional Alliance of Countries Calling for a Deep-Sea Mining Moratorium at the UN Ocean Conference in Lisbon. Fiji and Samoa were the first countries to join the Alliance, followed by the Federal States of Micronesia. The European Parliament has reiterated its call for the European Commission and Member States to support an international moratorium. In June 2022 the European Commission published the EU agenda on International Ocean Governance, in which it

---

[ii] https://investors.metals.co/news-releases/news-release-details/metals-company-engages-bechtel-support-noris-commercial-contract
[iii] International Seabed Authority. https://www.isa.org.jm/exploration-contracts
[iv] https://www.savethehighseas.org/2021/09/08/reaction-iucn-congress-votes-yes-to-a-moratorium-on-deep-sea-mining/

announced its intention to "*prohibit deep-sea mining until scientific gaps are properly filled, no harmful effects arise from mining and the marine environment is effectively protected*".[v]

By the end of 2022, many Pacific, Latin American and European countries had called for a precautionary pause, moratorium or complete ban on DSM due to a lack of scientific data on the areas of the seabed targeted for exploitation and the potential risks and impacts of DSM. This includes countries such as Germany and France, that previously voted in support of the advancement of DSM and sponsor mineral exploration contracts in the deep sea,[vi] with French President Emmanuel Macron calling for an outright ban on DSM at the UNFCCC COP27 in November 2022. Most recently, Canada has announced a moratorium on DSM in territorial and international waters.[vii] Some countries, including the United Kingdom, Norway, Singapore, India and the Republic of Nauru, have refrained from supporting a precautionary pause, and focused instead on the need to make progress towards finalising the regulations.[viii] Other member states of the ISA Council have indicated they would not approve mining contracts until such time as sufficient environmental protections are in place.[ix] Increasingly, concerns about the development of DSM are also being supported by private sector organisations.[5]

Global commitment to the conservation and sustainable management of the ocean is reflected, for example, in the adoption of a target to protect 30% of the ocean by 2030 in December 2022 at the Convention on Biological Diversity's Fifteenth Conference of the Parties. A UN agreement on the conservation and sustainable use of marine biodiversity in areas beyond national jurisdiction was also finalised in March 2023, further demonstrating the commitment of governments around the world to protect and prioritise the health of our ocean[1,x] Inclusion of the ocean in international climate discussions (at the UNFCCC) has also been growing and was first reflected in the wording of the COP 26 final declaration in 2021 and reiterated following COP27 in 2022 with the preamble recognising: *"the importance of ensuring the integrity of all ecosystems, including in forests, the ocean and the cryosphere, and the protection of biodiversity"* and emphasising the importance of protecting, conserving and restoring nature and ecosystems, including forests and other terrestrial and marine ecosystems, to achieve the long-term global goal of the Convention by acting as sinks and reservoirs of greenhouse gases and protecting biodiversity, while ensuring social and environmental safeguards (para 2).[xi]

---

[v] Joint communication to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Setting the course for a sustainable blue planet – Joint Communication on the EU's International Ocean Governance agenda. June 2022. https://oceans-and-fisheries.ec.europa.eu/system/files/2022-06/join-2022-28_en.pdf
[vi] https://www.reuters.com/business/sustainable-business/germany-calls-precautionary-pause-deep-sea-mining-2022-11-01/
[vii] https://www.nationalobserver.com/2023/02/09/news/canada-declares-moratorium-deep-sea-mining-global-conservation-summit
[viii] https://dsmobserver.com/2022/12/deep-sea-minings-rapid-technological-progress-is-met-with-increased-calls-for-a-precautionary-pause-at-the-closing-meeting-of-the-27th-session-of-the-international-seabed-authority/
[ix] https://www.bloomberg.com/news/articles/2022-11-07/more-governments-are-turning-against-the-rush-to-mine-the-deep-sea?leadSource=uverify%20wall&utm_source=Deep-Ocean+Stewardship+Initiative&utm_campaign=5977621177-EMAIL_CAMPAIGN_21_aug_2020_COPY_01&utm_me
[x] https://www.un.org/bbnj/
[xi] https://unfccc.int/topics/ocean

STATE OF KNOWLEDGE OF DEEP-SEA ECOSYSTEMS

Key points:

Despite the rapid increase in research, our knowledge of the deep sea remains nascent and very much in a discovery phase[6]: documenting species, community structure and biogeography[3] and with unique deep-sea ecosystems and species new to science continuously being discovered.[7]

In this vast and interconnected environment, there remains a dearth of basic information about all deep-sea ecosystems targeted and/or potentially affected by DSM[7] including ocean midwaters.[8] Not only are species and communities yet to be discovered or formally described, their ecology, interactions, and roles in ecosystem function and the provision of services are poorly understood or as yet unknown.[6–8]

Even the deep-sea habitats that have been the focus of research are still characterised by a paucity of information.[7] Uneven coverage and patchiness of scientific knowledge continues to be a constraint, and is a particular concern given that some of the most studied areas do not coincide with the location of exploration contracts for DSM.

In this section we highlight some of the findings from the latest science and conclude that there remains insufficient baseline information to enable evidence-based decision-making with regards to DSM. For a systematic review of current knowledge and gaps in current understanding of deep-sea environments see Amon et al. 2022.[7]

New studies continue to highlight just how little we know about the deep ocean

Since the release of Fauna & Flora's report in 2020, new studies continue to reveal the extraordinary diversity and complexity that exists in the deep sea. Sediment diversity in the deep ocean, for example, has been shown to be at least threefold that in pelagic realms with nearly two-thirds represented by abundant yet unknown eukaryotes.[9] It has been described as one of Earth's richest ecosystems and fossil archives with a strong connection to the water masses above.[9]

With more than 75 per cent of the seafloor unmapped and unobserved[xii] and less than 1 per cent of the deep ocean explored, we know less about the deep sea than any other place on the planet.[6] In a decade, the number of known active vent fields has doubled and it is projected that two thirds of all hydrothermal vent fields are yet to be discovered.[10] The latest research continues to emphasise just how little we know about life in the deep sea[9,11,12] (see also Box 1). Yet to make informed decisions that take into account effects from the full gamut of impacts arising from DSM, we need to understand all size classes of fauna from microbes to megafauna, including those most dependent on the resources targeted for mining but also the species and communities living in connected benthic and pelagic realms that may also be affected.

[xii] Seabed 2030 (no date) *About the Seabed 2030 Project*. https://seabed2030.org/mapping-progress (Accessed: 7 November 2022).

Box 1: Species discoveries, diversity and rarity in the Clarion Clipperton Fracture Zone (CCZ)

In the CCZ, where 17 exploration contracts for polymetallic nodules have been issued, there is comparatively more taxonomic and ecological information than for other nodule regions. Here studies consistently reveal very high levels of diversity.[6,7,12–16] Approximately 70-90 per cent of species collected in the CCZ are new to science[6], including the discovery of new genera.[7] Scientists expect many more species to be discovered, particularly in areas that have received little scientific attention to date but also at sites that have already been sampled.

Species are diverse and rare[15,16] and may have restricted ranges (≤200 km) or limited dispersal modes.[7,15–17] Rare taxa may fulfil unique functions, contribute to higher ecosystem functioning[18] and be more prone to extinction[19], particularly where species are restricted to mining contract areas.

Application of molecular tools further identifies hidden or cryptic diversity in the deep sea[20] which refers to the identification of species or lineages that are morphologically indistinguishable but genetically distinct and only detectable through molecular data. Such approaches are being used to complement traditional morphological methods to support the assessment of deep-sea biodiversity. As methodological and technological advances are made, studies indicate that even some of the more conspicuous species in abyssal plains have been underestimated, with a single study increasing the number of ophiuroid (brittle star) species reported from polymetallic nodule fields of the Pacific by 433%.[12]

Uneven coverage and patchiness of scientific knowledge continues to be a constraint and the most studied regions are not necessarily the most biodiverse nor coincide with areas targeted for mining.[7,10] In the CCZ, for example, scientific knowledge is biased towards the eastern half[10,16] limiting understanding of trends relating to depth and productivity gradients[21] whilst inactive vent habitats targeted for polymetallic sulphide mining have received little scientific attention compared to hydrothermally active vents.[22] Among regions with polymetallic sulphide exploration contracts, the northern Mid-Atlantic Ridge has received comparatively more scientific attention than the Indian Ocean Ridge yet contracts for exploration have been issued in both.[7] Seamounts are the least explored habitats and baseline conditions are not even partially characterised.[7] Across all deep-sea environments information about the pelagic ecosystems above the seabed remains extremely limited[7,8] and all regions targeted for mining require further study to gather enough baseline information to enable evidence-based management.[7]

The roles of deep-sea fauna in ecosystem functions, including carbon fixation, cycling and storage, productivity and metal cycling are the focus of scientific attention, yet are not well understood. For example, the importance of deep-sea microbial communities, whose biomass is estimated to account for between 10 and 30% of Earth's living biomass[11], in the food web and in biogeochemical processes of carbon, metal, nitrogen and sulphur cycling has been emphasised.[23] New research reinforces the key role of the microbial community in benthic carbon cycling at abyssal depths[24] and in the origin of chemical elements in polymetallic nodules.[25] To understand ecosystem health and function we need to consider species interactions within and between size classes and better understand microbial involvement in these interactions.[26]

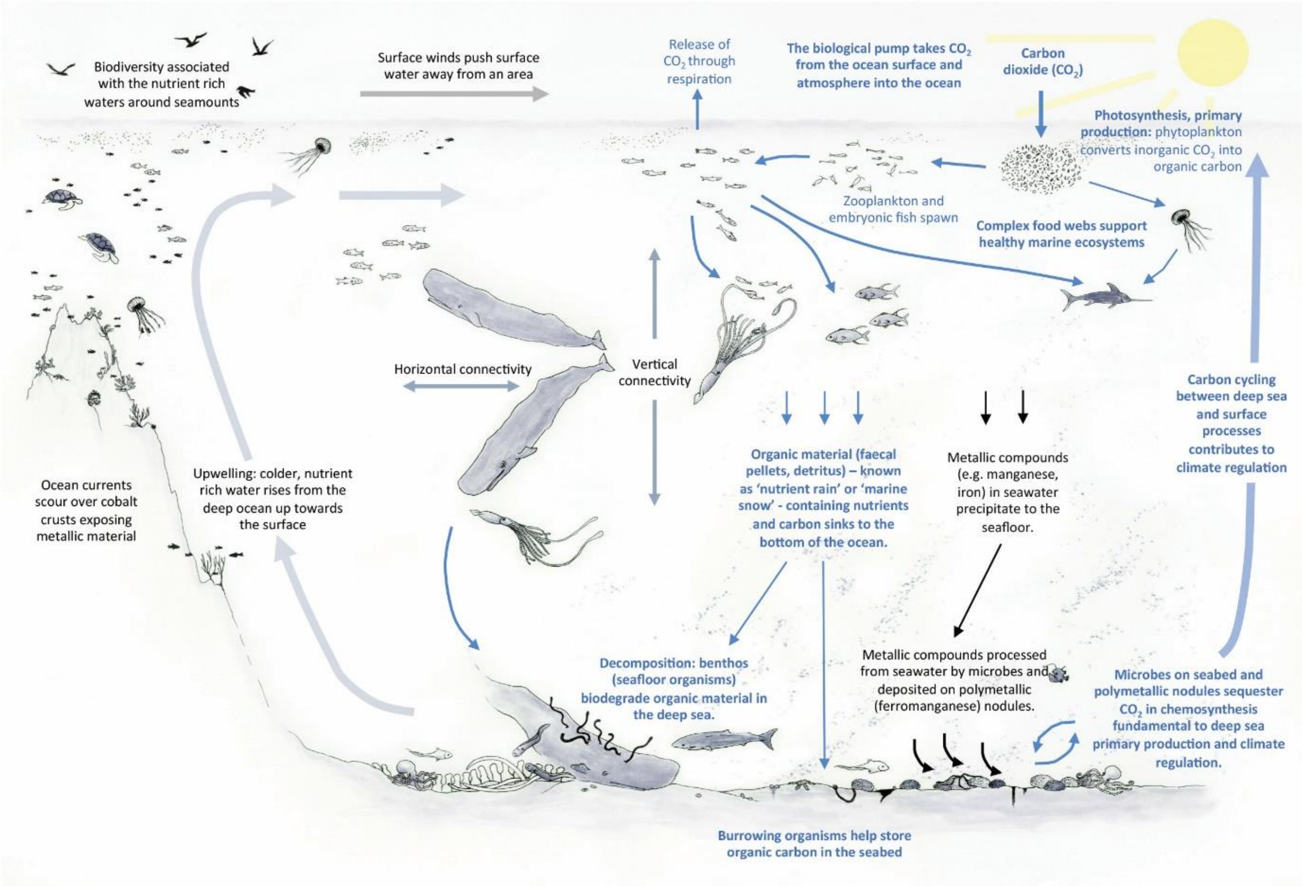


Figure 1: Illustration of oceanic processes including primary productivity and the biological pump, and connectivity. *Illustration not to scale.*

Heterogeneity and zones of influence in the deep sea

To assess and monitor changes that might result from DSM it is necessary to understand natural conditions and variability over space and time. This is recognised in the ISA's *'Recommendations for the guidance of contractors for the assessment of the possible environmental impacts arising from exploration for marine minerals in the Area'* (ISBA/25/LTC/6/Rev.1, 30 March 2020, para. 14). However, our understanding of natural variability in deep-sea environments remains limited.[7]

In the deep sea, as on land, broad ecosystem classifications belie the immense variation that exists within ecosystem types. As Thaler & Amon[10] explain:

> *"Just as 'forest' describes ecosystems ranging from boreal forests to tropical rain forest, 'hydrothermal vent' describes a suite of deep-ocean ecosystems united by a shared dependence on chemosynthetically derived primary production and above-ambient temperatures but diverse in their composition and connection to one another."*

Since 2020, studies have continued to uncover high levels of heterogeneity within and between deep-sea environments, on multiple scales and across many different variables,[7] such that generalisations from one area to another cannot be made. Scientists are only just starting to elucidate some of the factors that may be driving biodiversity patterns[12], which include habitat heterogeneity and, with the exception of chemosynthetic ecosystems, food supply from particulate organic carbon produced in the ocean's sunlit layer that sinks to the seabed. At active hydrothermal vents new studies highlight the influence of vent plume fallout (when particles leave the plume) on benthic species composition in sediment.[27] The potential significance of invisible underwater soundscapes in shaping deep-sea biodiversity has also been suggested though there remains a lack of soundscape baselines for the deep ocean.[28]

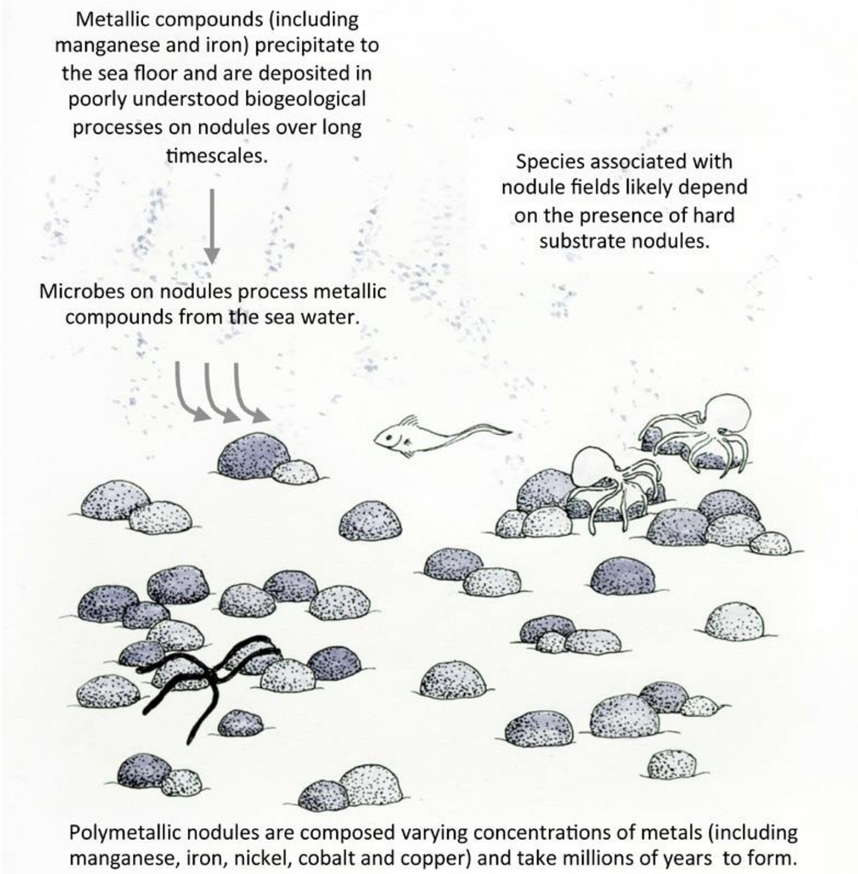


Figure 2: Polymetallic nodules associated with abyssal plains and processes contributing to their formation. *Illustration not to scale.*

New studies reinforce the importance of the resources targeted for extraction by DSM companies for biodiversity. For example, polymetallic nodules have been shown to provide distinct habitat for species across all size classes[2,23] whilst the latest science reveals the critical importance of nodules for food web integrity such that their removal will likely result in reduced local benthic biodiversity.[29] Nodules act as a driver of biodiversity, abundance and ecosystem function[7], with nodule density and size found to be key factors influencing abundance, diversity and community structure in a range of taxa.[15,16,18,23,30]

The influence of deep-sea ecosystems on surrounding benthic and pelagic communities has been revealed. Chemosynthetic ecosystems (hydrothermal vents and hydrocarbon/cold seeps), for example, have been found to influence larger “transition zones” that vary in extent both horizontally and vertically and include non-chemosynthetic regions.[31,32] Transition zones support a mix of chemosynthetic species as well as those that typically rely on food supplied from photosynthetic production in sunlit waters near the surface.[32] During times of food scarcity benthic organisms in transition zones may be supported by chemosynthetic energy sources: a finding that has implications for our understanding of chemosynthesis-based carbon in food webs and energy flows[33] as well as the resilience and management of benthic communities in these regions. For active vent systems, studies further suggest that the direction, composition and volume of the vent plume may influence the degree of connection of active vent ecosystems to their non-vent surroundings.[34] Understanding and taking into account connections and interactions in the transition zone and with pelagic communities is essential when assessing risks and impacts of DSM for polymetallic sulphides and in the face of climate change effects.[31,32]

Climate change and the deep sea

The essential role of the ocean in regulatory systems operating at a planetary scale (i.e. global cycles of carbon, nutrient, and metal cycling) continues to be emphasised. The specific contributions of deep-sea habitats remain poorly understood but new studies have begun shedding light on these connections.[35] Since the publication of Fauna & Flora's 2020 assessment leading experts have synthesised the latest science with particular attention given to the role of the deep ocean in global carbon cycling and mitigating the effects of climate change, as well as the likely effects of climate change on deep-sea ecosystems.[36]

The ocean absorbs and stores over 91% of the excess heat from global warming[37,38] regulating the Earth's climate and buffering the planet from the effects of climate change. Deep-sea environments contribute significantly to the exchange of carbon over long timescales through the vast seafloor area they encompass.[39]

Marine sediments have been found to be one of the most expansive and critical carbon reservoirs on the planet, with deep-sea sediments at water depths greater than 1000 metres storing nearly four-times as much carbon compared to sediments underlying shallow seas and with 75% of marine sediment carbon stored within the sediments of the abyss/basin zones.[40] The sheer volume of carbon stored in unprotected marine sediments emphasises the importance of their long-term protection: breakdown of even a small fraction of stored marine sediment carbon could exacerbate climate change.[40]

The critical role of deep-sea species and ecosystems in the cycling and storage of carbon continues to be highlighted[9,39,41] including through the daily vertical migration of mesopelagic fish and zooplankton through the water column[42] and the sinking of carcasses that export carbon from the sunlit zone to the seabed.[43,44] New studies further showcase the importance of eukaryotic plankton diversity (including taxa known to be important in the biological carbon pump and others previously overlooked) reaching the deep-ocean sediment at a global scale and thus driving the biological transfer of atmospheric carbon to the seafloor.[9]

A growing body of research shows climate change impacts occurring at unprecedented rates in the deep ocean, leading to a less oxygenated, more acidified, warmer deep ocean, with potentially devastating consequences for deep-sea biodiversity and associated ecosystem functions and services.[45–50] The extent to which climate change effects will impact on oceanic carbon cycling remains unknown. Understanding the effects of non-mining impacts, including climate change, is crucial in determining the full implications of impacts arising from DSM.

Many species in the deep sea are expected to be highly sensitive to disturbance, having evolved in a stable environment within a narrow temperature range. Even small changes in conditions could have serious effects on deep-sea species.[36] Recent studies point out that even if global temperature rise is limited to under 2˚C the deep ocean will continue to warm, with potential for major impacts on the deep ocean and its biodiversity.[50] The effects of climate change in surface waters are expected to lead to a reduction in particulate organic carbon flux to the seafloor. This will directly affect deep-sea species reliant on organic matter from surface production.[39]

Recent climate change has already contributed to changes in the distribution and abundance of many benthic taxa and altered the transfer of materials between ocean and sediment layers, with implications for carbon cycling and storage and the cycling of other elements in marine systems.[39] Projected climate velocities, which describe the speed and direction a species would need to move to remain within its climatic niche[51], in the deep sea are expected to accelerate with climate velocities at depths greater than 4,000 metres projected to reach 5.5 times the rates currently experienced at the surface by the end of the century.[36,50]

Insufficient baseline information for all regions targeted for mining

With growing insight comes increasing awareness of how little we know. Robust baselines are essential for determining the risks and impacts of DSM. The systematic review undertaken by Amon et al.[7] concluded that all regions, including the seafloor and water column, both within and outside contract areas require further sampling to gather enough baseline information to enable evidence-based decision-making on environmental management.

As technologies and methods advance, parameters and approaches are being identified to reduce risks of underestimating different aspects of the biodiversity baseline. For example, in monitoring the seafloor using autonomous underwater vehicle image analysis altitude is a key factor, with images taken above eight metres underestimating megafauna density by almost 50%.[30] Improved understanding of transition zones around chemosynthetic ecosystems has also emphasised the need for combined methodologies that not only utilise remote sensing and visual surveys but direct measurements derived from physical sampling of sediments, water and the living organisms associated with them.[32] Research is ongoing to determine the deep-sea ecological variables that need to be incorporated in developing a baseline and the role of different taxonomic groups as indicators for monitoring change.[11,52]

There is as yet no baseline standard or criteria for determining adequacy and quality of baseline information.[2,53] This poses a significant risk. In the absence of agreed quality criteria, an inadequate baseline may still satisfy legal requirements.[53]

RISKS AND IMPACTS OF DSM

Key points:

A comprehensive understanding of the deep-sea environment and the likely impacts of DSM is required to determine whether and under what conditions DSM operations comply with the ISA's obligations to prevent *'serious harm'* and ensure the *'effective protection of the marine environment from harmful effects'* in accordance with the UN Convention on the Law of the Sea.[7]

Fauna & Flora's 2020 assessment concluded that based on the available scientific evidence, impacts of DSM may be "**extensive and irreversible, permanent and immitigable**". Since then, new studies continue to reinforce this conclusion, highlighting impacts on benthic and pelagic ecosystems and very high levels of uncertainty associated with DSM.

Profound gaps in basic knowledge about the deep sea constrain our ability to predict how species, ecosystems and processes will respond to impacts, what their potential for recovery might be and over what timescales, and the implications for ecosystem functions and services that are in themselves poorly understood. This all also limits ability to set environmentally acceptable threshold levels based on scientific evidence.[54]

Uncertainties and unknowns remain relating to the spatial and temporal extent of DSM impacts, their environmental effects and potential for synergistic and cumulative impacts.[3,6,36] As scientific understanding of the deep sea continues to grow, so too does recognition that impact assessments based on current knowledge may considerably underestimate the magnitude of effects from DSM impacts, particularly when coupled with existing and emerging stressors in the deep sea.

Scientists conclude that if permitted to go ahead, the nascent DSM industry would "*lead to biodiversity loss and disruption of ecosystem services on an enormous spatial and temporal scale*",[55] with species and functions lost before they are even known and understood.[35] When considered alongside the infancy of understanding of the deep ocean and the role it plays in regulatory systems at a planetary scale, the importance of precaution cannot be overstated.

The recently published evidence review commissioned by the UK Government[2] concluded that "*we simply lack the evidence base on which to meaningfully evaluate impact assessments during licensing process*"… [and] …"*cannot currently assess what level of harm is serious and whether serious harm will occur*." The authors further suggest that based on current knowledge DSM is likely to meet the UN Food and Agriculture Organisation bottom fishing criteria for causing significant adverse impacts and conclude that "*long-term (>centuries) and broad-scale (>1000 km^2) impacts of DSM are likely*"[2].

Fauna & Flora's 2020 report documented the main risks and impacts to arise from DSM activities, based on the available information at that time, which broadly involves the removal and destruction of seafloor habitats and communities, consequences of sediment plumes at the seafloor and in the water column extending impacts horizontally and vertically, noise and light pollution, contaminant releases and changes to water properties.

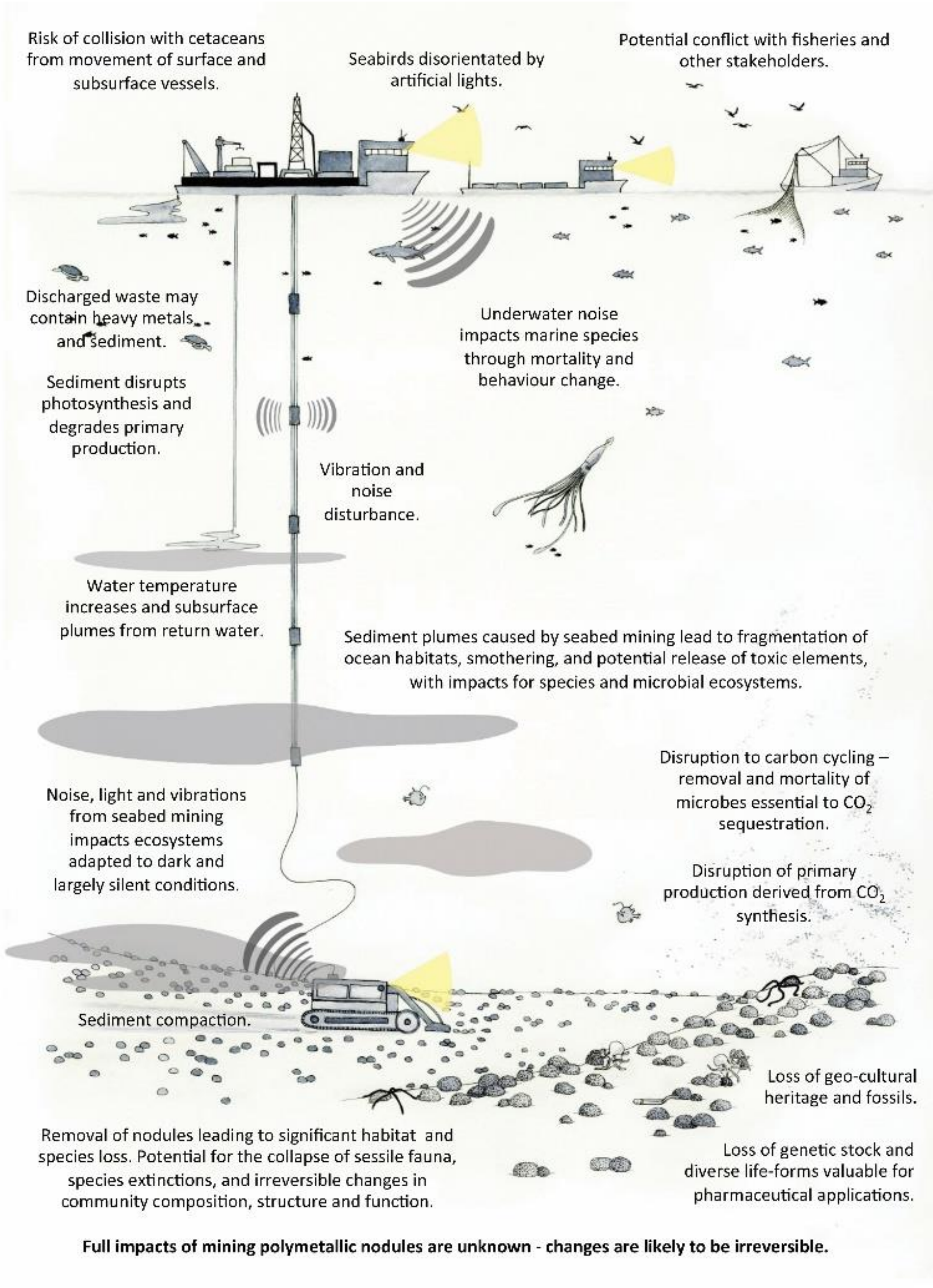


Figure 3: Risks and impacts of mining of polymetallic (ferromanganese) nodules.
Illustration not to scale. Adapted from Miller, Thompson, Johnston & Santillo (2018): https://doi.org/10.3389/fmars.2017.00418 CC BY 4.0

New studies contribute to a growing evidence base that emphasises the sensitivity of deep-sea species and ecosystems to disturbance, the severity and extent of effects from sediment plumes and other sources of impact and implications for ecosystem functions and services. Effects of DSM impacts are found to be long-lasting and continue to call into question the potential for natural recovery post-mining.

Experts have analysed and synthesised the available evidence, identified gaps, methods and misconceptions that may contribute to the underestimation of impacts, and improved understanding of what we don't know and need to know.[2,3,7]

> *"Despite an increase in deep-sea research, there are few categories of publicly available scientific knowledge comprehensive enough to enable evidence-based decision-making regarding environmental management, including whether to proceed with mining in regions where exploration contracts have been granted by the International Seabed Authority. Further information on deep-sea environmental baselines and mining impacts is critical for this emerging industry".(Amon et al 2022)[7]*

A roadmap for closing key scientific gaps relating to DSM has been put forward by Amon et al.[7] which anticipates a decade or more for each resource in each region. Addressing gaps will require substantial time, investment, and a capacity-intensive, coordinated scientific effort. The importance of primary research to inform decisions to protect the deep-sea environment, and for data collection independent of the extractive industry and for purposes broader than mining has been emphasised.[36,56]

In parallel, the development and testing of mining technology and methods are ongoing, contributing to uncertainties and already impacting the deep seabed. In late 2022, a large-scale DSM trial by The Metals Company subsidiary Nauru Ocean Resources Incorporated (NORI) and offshore partner Allseas removed an estimated 4,500 tonnes of nodules, transporting them up a 4.3 km riser system to the surface production vessel.[xiii] The approval of the mining trial has been questioned and concerns raised about the ISA's lack of transparency.[xiv]

Limited visibility and a lack of publicly accessible data on methods and technologies as well as from mining-equipment tests makes quantitative assessment of risks and impacts and predictions of the magnitude of impacts extremely challenging.[7,57] Full-scale systems and equipment reliability in deep waters and over long periods still require rigorous field testing.[2]

Evidence mounting for widespread and severe effects on biodiversity

New studies are helping to elucidate the potential scale, duration and effects of certain DSM impacts. The direct footprint for nodule mining is expected to be the largest of the three targeted resources, extending tens of thousands of square kilometres.[35] Disturbance from a single mining operation in the CCZ could affect an estimated 32,000 km^2 over 20 years whilst, collectively, mining in all current contract areas across the CCZ could remove, bury and/or smother over half a million square kilometres, constituting a substantial proportion of nodule habitat in the CCZ.[3]

As new evidence emerges, the far reaching effects of noise and sediment plumes from mining activity are being investigated. Whilst knowledge of the sources of acoustic energy from DSM remains incomplete, new research suggests that the noise generated by a single

[xiii] https://www.rnz.co.nz/international/pacific-news/478791/ocean-miner-completes-controversial-pacific-trials

[xiv] In a letter to the ISA Legal and Technical Commission, the ISA Secretariat and the permanent mission of Nauru to the UN, the Deep-Ocean Stewardship Initiative (DOSI), articulated its concerns over the ISA's Legal and Technical Commission recommendation on the Environmental Impact Statement submitted by NORI to conduct mining tests in the Pacific Ocean. See: https://www.dosi-project.org/wp-content/uploads/LetterDOSI_NORI_EIS_LTCrecommendation.pdf

polymetallic nodule mining operation could extend hundreds of kilometres whilst noise from each of the mining operations in the CCZ combined might lead to 5.5 million km^2 being filled with sound at levels above gentle-weather ambient conditions.[58] In other deep-sea environments, additional sources of noise from drilling, cutting, as well as discarding of cuttings could **mask the natural deep-sea soundscape and adversely affect marine mammals and other species in and around mining areas**.[7] The full implications of such noise pollution for deep-sea biodiversity are not yet known. Testing of reduced-scale, incomplete, prototype mining machines is underway but sound source characteristics from internal risk assessments or pilot studies have not been published.[58]

No information is available on deep-sea species sensitivity and responses to noise. Without sunlight, many species rely on sound and vibrations and may be particularly vulnerable to noise from human activities.[58] Resilience of deep-sea habitats may also be affected.[28]

Recent studies contribute to a growing evidence base on the effects of sediment plumes at the seabed and in midwaters.[8,54,59] DSM generates plumes both from the collector vehicles operating on the seabed, and from the discharge flow released from the surface vessel after dewatering of the ore where the polymetallic material (e.g., nodules, broken pieces and particles) are separated from the seawater and sediment which are then disposed as waste back into the ocean. Deep-sea organisms are expected to be highly sensitive to the effects of sediment plumes as many exist in an environment in which the water is typically very clear. Plumes, which may contain elevated metal concentrations, can smother organisms, clogging respiratory and olfactory surfaces, and weaken organisms leading to mortality, reduce visual communication and bioluminescent signalling in turn affecting the ability of animals to capture prey and reproduce, affect species interactions and potentially limit recolonisation of disturbed areas.

The horizontal spread of plumes is likely to be more extensive during nodule mining compared with cobalt-rich crust or sulphide mining, with plumes from all forms of mining adversely affecting both benthic and pelagic ecosystems. The importance of considering effects through the entire water column has been stressed.[8,60] [61] demonstrate the effects of plumes resulting from the release of rejected mining material, wastewater and sediment in midwaters, revealing that **it can take about one year for a 10 μm sediment particle to settle from the midwater column to the seabed, over which time it can travel ~1,000 kilometres in any direction**. It is challenging to quantify long-term effects but for a 20-year commercial mining operation, Muñoz-Royo et al.[61] indicate that sediment and fines could settle over an area of a few million square kilometres - comparable in scale to the CCZ.

As midwaters are in continuous motion and midwater communities can mix freely across boundaries, it will not be possible to contain the spread of mining impacts nor the amount of time that marine organisms are exposed to the effects of plumes in midwaters which may go beyond that experienced at the seabed.[8] Simulation experiments also suggest that polymetallic nodule mining will have affect surface phytoplankton biomass with the growth of phytoplankton affected by metal concentrations and turbidity.[62] Ecological baselines for midwater ecosystems do not exist, yet are essential in determining the three-dimensional spread and persistence of plumes over time.

Particle size plays an important role in determining the speed of settling, with larger particles settling faster. In nodule areas the seabed is dominated by fine sediments[63] which, even in small concentrations, can lead to sediment remaining in suspension for longer periods of time and with potential to extend over larger areas, with background turbulence processes, including turbulence from mining operations, playing a role in the evolution of the seabed plume.[64] Developing an accurate understanding of particle size distribution in the plume is essential to avoid orders of magnitude underestimations of extent metrics.[64]

Metals are expected to remain in the water column much longer than sediments - potentially 100 to 1,000 years.[8] Studies also show different metals exhibit variation in responses during the resuspension process,[65] with metallic content showing different dispersion and uptake dynamics.

Although threshold levels are unknown, studies emphasise the sensitivity of nodule habitats and species, particularly in the CCZ, to even low sediment concentrations given extremely low natural sediment concentrations even near the seafloor.[3,8,60,66,67] Effects will be exacerbated by the scale of mining and persistence of plumes over months to years.[3] Kim et al.[68] further suggest that not only the sediments around the nodules but also sediments within the nodules will contribute to the discharge. Therefore, even if technological advances are effective in rejecting or avoiding sediment at the seabed and only collect nodules, the discharged materials might still contain sediment particles. Understanding of the degradation products of polymetallic nodules requires further research.

At seamounts, a new study suggests plumes generated by mining of cobalt crusts may be more localised[69] whilst others highlight risks posed by dispersal of plumes directly into the water column with implications for pelagic biota and potential for heavier particles to accumulate and lead to submarine sediment movements.[63]

In chemosynthetic ecosystems targeted for mining of polymetallic sulphides, large horizontal and vertical plumes that can travel more than 100 kilometres and impact more than 10,000 km^2 have been projected based on modelling in the Azores.[70] Plumes may disperse beyond licensed mining areas and across important transition zones, reaching flanks and summits of nearby topographic features and extending through the water column with implications for marine food webs and ecosystem function in benthic and pelagic ecosystems.

Recent studies shed new light on the responses of some deep-sea species to plumes and emphasise taxon-specific responses. Spatial variation of benthic communities at active hydrothermal vents has been found to be influenced by vent plume fall-out, indicating that plumes created through the mining of polymetallic sulphide deposits will affect these unique benthic communities.[27] Different organisms are also expected to exhibit varying levels of tolerance to plumes: impacts for some may only become apparent after a prolonged period, others may be more or less sensitive to particle load compared with low-level toxins.[30] For example, *ex-situ* studies demonstrate that even low concentrations of polymetallic sulphide particles in plumes can result in detrimental mechanical and toxicological effects. Octocorals, for example, exhibited rapid physical accumulation of particles in their tissues limiting feeding, as well as bioaccumulation of copper (which refers to the build-up of copper in individual organisms), resulting in death within a month.[71] Copper is one of the most toxic metals to be released into seawater during polymetallic sulphide mining operations with a separate study showing that cold water corals are unable to recover from exposure.[72] The potential for delayed mortality and ecosystem impacts is highlighted.

Many operational uncertainties and unknowns remain that could influence the nature of plumes generated by DSM activity and their effects; from the design of mining collector vehicles[73], waste profiles and volumes of waste production[74], to the production rate of plumes and whether these will be constant or vary. There are no existing standards for managing deep-sea plume composition, volume or behaviour.[73] Following the precautionary principle it has been recommended the threshold for acute plume impacts is set very close to natural background levels.

Effects will be long lasting with implications for resilience and regulatory functions

Since Fauna & Flora's assessment, additional studies have reported on the effects of simulated mining disturbance in nodule areas for ecosystem recovery.

After a quarter of a century, plough tracks were still visible, indicating sites where sediment was either removed or compacted, and carbon cycling in benthic food webs, biogeochemical cycling, and rates of organic matter remineralisation (which refers to the breakdown or transformation of organic matter into its simplest inorganic forms) had still not recovered.[75] Microbial activity was reduced up to fourfold in affected areas with growth estimates indicating that microbially mediated biogeochemical functions need over 50 years to return to undisturbed levels.[75] Food-web functioning, especially the microbial loop, had not recovered, and variability in recovery was reported among different faunal food-web compartments with small mobile fauna recovering faster than larger sessile fauna[24]. Modern patterns of *Paleodictyon* species (a form of living fossil) are impacted by physical seafloor disturbance and densities on disturbed sediments had not recovered to undisturbed levels.[76]

Recovery from industrial scale DSM cannot be directly extrapolated from small-scale disturbance results[24], with recovery expected to be slower given the longer duration and larger spatial scales of impacts.[2] Where connectivity to unaffected areas is reduced this will further hinder recovery processes.[24] Unlike the disturbance experiments, which ploughed nodules beneath the surface, mining will remove nodules, destroying nodule-obligate fauna and changing community composition. Experts conclude that industrial-scale polymetallic nodule extraction will impair the microbial loop and modify the cycling of carbon, metals and other elements that these key organisms carry out.[23,24] Regrowth of nodules is expected to take millions of years and without the hard substrate provided by the nodules, nodule ecosystems may never recover to pre-impact state. Impacted areas are more likely to be replaced with different faunal communities, functions and services with timescales dependent on the recovery of underlying biogeochemical fluxes and processes, in which impacted microbial communities play a significant role.[77] Recovery of organisms dependent on cobalt crusts of seamounts could require thousands to millions of years, given the very slow rate of crust formation.[35]

Resilience to mining disturbance is generally expected to be low. The deep ocean (with some exceptions) is a very stable environment in which organisms have evolved to live within a very narrow range of physico-chemical conditions.[36] Species are generally long lived, with low reproductive output, and are late to reach maturity, reducing their ability to cope with change and increasing vulnerability to disturbance. Most deep-sea fauna are also food limited and may have less energy to respond to disturbance.[66] Therefore, disturbance from the combined effects of DSM, as well as from climate change and other stressors, could be particularly severe. To survive, some species are expected to be forced to migrate away from impacts leading to changes in community composition and structure, and ecosystem function and with implications for ecosystem recovery. With many rare and restricted range or endemic species the risk of extinctions is high. The loss of biodiversity is expected to further reduce overall ecosystem resilience.[52]

Mining will contribute to emissions and may disrupt carbon cycling

DSM impacts are not limited to below the sea surface, with DSM operations expected to generate considerable greenhouse gas emissions. A recent study estimated that a potential nodule mining operation in the CCZ operating at 5,000 metres depth with an annual production of 3 million dry tons could emit between 81,294 and 474,479 tons of CO_2.[78] Integrating emissions from deep-sea extractive activities, considering the entire nodule to commodity cycle, into the regulatory regimes concerned with climate change, air pollution and shipping is essential.[36]

Mining will disturb marine sediment in the deep sea over vast areas and remineralisation of even a small fraction marine sediment carbon stocks could exacerbate climate change.[40] Mining will lead to habitat removal, decline and loss of species and communities with critical roles in the cycling and storage of carbon, and disruption of regulatory function. Changes will persist over long timescales. Whilst it is not currently possible to ascertain the extent to which DSM might contribute to climate change through its impacts in the deep sea, Amon et al. conclude that "*there is potential for significant effects on carbon cycling and storage in the deep*."[36] While the science is still being developed to fully quantify the processes at play, the protection of carbon stored in the deep seabed and carbon cycling and storage processes is a potentially vital nature-based solution to climate change[79]; one that DSM is directly at odds with.[56]

Societal implications of DSM risks and impacts

Fauna & Flora's 2020 assessment featured research on the potential effects of DSM for ecosystem services such as fisheries, climate regulation, detoxification and nutrient cycling, as well as potential future biotechnical or pharmaceutical applications. The values of such ecosystem services in the deep ocean are not yet fully understood or quantified.[35] Societal implications (both substantive and procedural) of DSM are receiving more attention, with concerns raised for the realisation of human rights including the right to a clean, healthy and sustainable environment, and rights to health, the financial benefit sharing mechanisms, a lack of transparency and inadequate stakeholder engagement.

Proponents of DSM have utilised the absence of human habitation in the deep ocean to downplay the potential social or environmental consequences, particularly through comparisons to terrestrial mining.[74,80–82] However, the evidence review commissioned by the UK Government and published in 2022 emphasises that "*a comparison of terrestrial mining and deep-sea mining is extremely challenging and requires value judgements that in most cases cannot be clearly informed by evidence*".[2] Moreover, the adverse impacts of terrestrial mining cannot justify the risks posed by DSM.[83]

DSM may be located in the deep sea, thousands of metres below the surface, yet it has the potential to impact upon the seabed, water column, sea surface, air and land. Connectivity between the deep seabed and pelagic realm means effects do not adhere to the boundaries of mining contract areas and have the potential to affect vast areas including territorial waters. DSM is also connected to the land due to transportation and processing of the mined materials.[84]

DSM operations and their effects on deep-sea ecosystems are expected to have serious implications for human communities dependent on marine ecosystems. Midwater ecosystems, for example, represent more than 90% of the biosphere, contain fish biomass 100 times greater than the global annual fish catch, connect shallow and deep-sea ecosystems, and play key roles in carbon export and nutrient regeneration.[8] As emphasised in recent studies, DSM poses significant risks to midwater ecosystems[8,61] and the functions and services they provide to people including fisheries and carbon cycling and sequestration.[8] Concerns have also been raised that plumes from mining activity in the eastern CCZ could reach the coastal waters of Hawaii within just a few months.[xv]

DSM poses risks to food safety and security through impacts on marine life (particularly migratory fish stocks) and fisheries, and potential for metals and toxins to build up in marine

[xv] https://dsm-campaign.org/blue-peril/

food webs which could enter the human food chain. The latter may be elevated if plumes resulting from the discharge of waste water and material following dewatering of the ore are released near the surface or in midwaters.[8,85] The magnitude of human health risks like these is not known, but it is clear that the risks are not contingent on physical proximity to DSM activity. The potential for DSM to undermine full realisation of human rights to health obligates states to exercise precaution and to factor potential human rights impacts into their decision making concerning the development of a DSM regime.[85]

Concerns also relate to the development of financial mechanisms that appear to prioritise the enabling of DSM rather than delivering fair compensation for loss of resources.[6,56,86] The importance of safeguarding the deep ocean and ensuring that payment models reflect all costs and risks associated with DSM has been emphasised, as well as the interests of future generations in having a healthy and productive ocean to benefit from. Blue Marine Foundation[6] notes that beyond a small number of contractors and states holding ISA contracts, few others stand to benefit from DSM as mining may only generate small amounts of money for the ISA to redistribute.

Under the UN Convention on the Law of the Sea the deep seabed is to be managed for the benefit of all (hu)mankind. Yet to date, competition between contractors, data privacy, opaque processes and closed-door dialogue appear to be preferred over collaboration, open access data, participative stakeholder engagement and transparency.[4]

CUMULATIVE EFFECTS

Key points:

The combined effects of DSM (i.e., habitat removal/burial, sediment plumes, toxicity, noise and light pollution) **will occur in concert with existing and emerging stressors**, from overexploitation and pollution to climate change, with potential for increased synergistic effects on marine organisms, ecosystems and the functions and services they provide.[87] The cumulative and interactive effects of multiple stressors, biodiversity loss, and habitat destruction represent an increasing and unprecedented threat to the ocean.[46]

Fauna & Flora's 2020 report emphasised the need to assess and mitigate cumulative impacts, including those resulting from the effects of multiple mining operations as well as other human activities and climate change. The report highlighted potential for regional losses, reduced resilience, changes to community structure, genetic isolation, species extinction and heightened risk of species invasions.

Cumulative effects remain poorly understood, yet given the growing evidence base for the effects of individual mining impacts, the likelihood of serious adverse cumulative effects is even greater. Experts emphasise that such impacts could become more unpredictable over time, contributing to heightened uncertainty and potential exacerbation of mining impacts.[56] Changes to the chemistry underpinning deep-sea biological systems, for example, will not only disrupt the processes on which ocean productivity relies, but also give rise to knock-on effects that we cannot currently comprehend or predict.

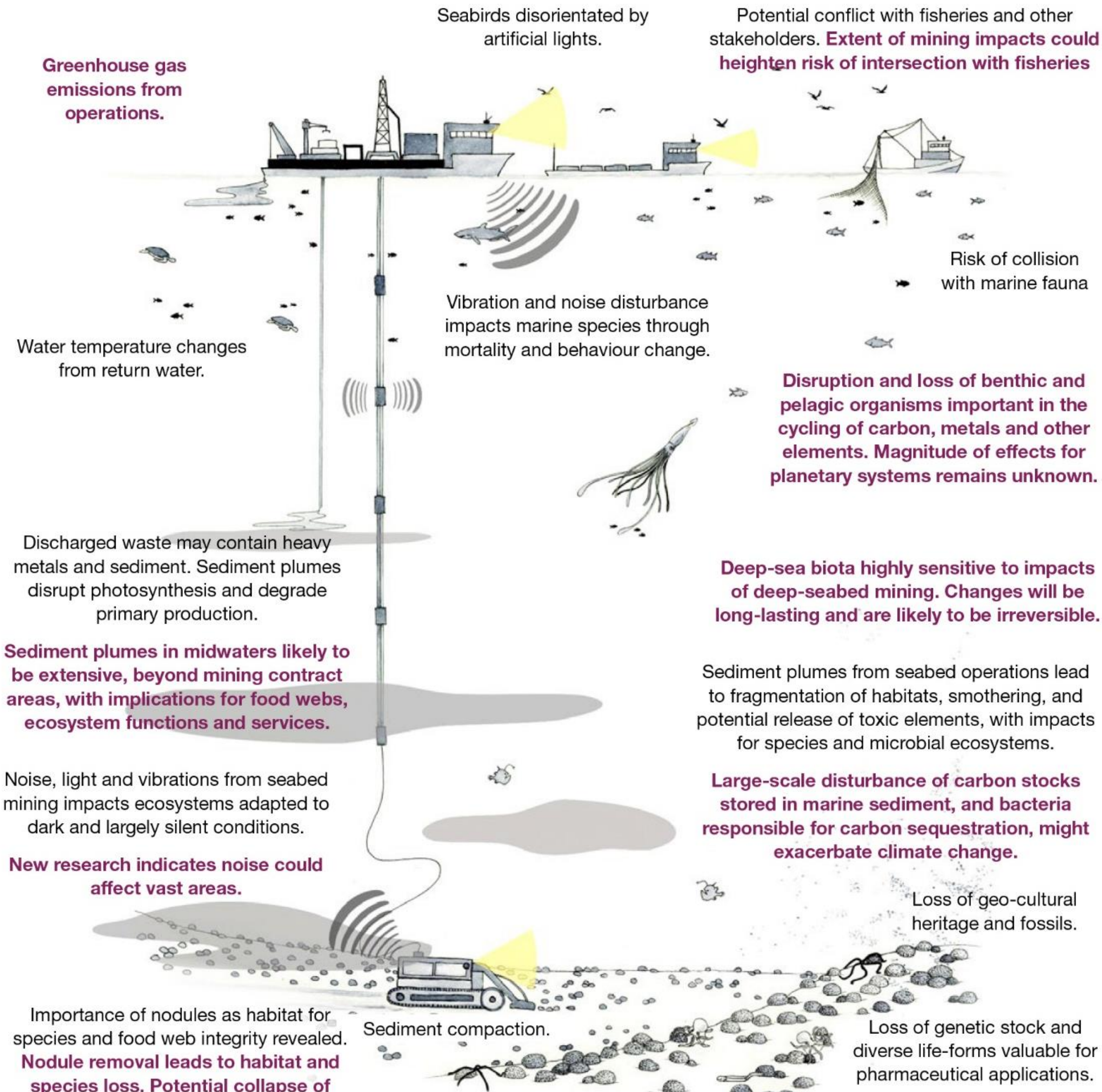
Mining impacts will interact with climate change

The impacts of DSM activities are expected to interact with climate change stressors, reducing the resilience of deep-sea organisms and ecosystems, and exacerbating impacts.[7,48] Though the full extent of climate change impacts on the deep ocean remains unknown[49], all deep-sea ecosystems will be affected and biodiversity decreases are ultimately expected.[48]

Climatic changes will reduce food supply (through declines in particulate organic carbon flux) **to the deep seabed, an already food-limited environment,** whilst increasing demand for food by deep-sea organisms is expected to accompany higher temperatures through increased metabolic rates.[24] However, under future climate scenarios such increases in demand cannot be met[24] compromising resilience and recovery. Overall, climate change is expected to slow recovery from disturbance in seamount and abyssal systems,[48] further limiting any potential for ecosystem restoration post mining.

Ocean warming, acidification and deoxygenation may affect the dispersal and toxicity of metals associated with the mining of polymetallic sulphides.[88] Climate-induced alterations to food webs and conditions in the deep sea are likely to increase the effects of metals and other contaminants in marine food webs through bioaccumulation (the process by which contaminants build up in individual organisms) and biomagnification (which occurs when that organism is consumed by one higher up the food chain resulting in contaminants passing from one trophic level to the next and increasing in concentration). This may exacerbate the effects of mining-related releases of metals or other contaminants (e.g., suspended sediments) with implications for human health if they affect seafood supply.[48] Temperature increases may facilitate invasions of deep-sea habitats by certain taxa increasing risks of introducing invasive species through DSM.

Lack of available scientific information on the deep sea, how organisms support deep-sea carbon cycling processes, climate change effects and how impacts of climate change, mining and other human activities may synergise, contributes to high levels of uncertainty and makes it impossible to quantify the magnitude of mining effects.[7,36,48] With options to mitigate the effects of climate change in the deep sea extremely limited[48], a precautionary approach to any activities that adversely impact deep-sea habitats is of paramount importance.



FULL IMPACTS OF MINING POLYMETALLIC NODULES ARE UNKNOWN.

Deep-seabed mining will not occur in isolation. The effects of climate change and mining will interact and may exacerbate mining impacts. Risks and uncertainties around the cumulative effects of human activities and other stressors are very high.

Growing concern around implications for human rights, including the right to health, and to a clean, healthy and sustainable environment.

Figure 4: Risks and impacts of mining of polymetallic (ferromanganese) nodules, updated to show new evidence accentuating these risks and impacts (shown in purple text).
Illustration not to scale. Adapted from Miller, Thompson, Johnston & Santillo (2018): https://doi.org/10.3389/fmars.2017.00418 CC BY 4.0

Interaction with other sectors and emerging threats

If permitted to go ahead, DSM will be operating alongside other sectors in the blue economy and their impacts. The potential intersection between DSM and fisheries in the High Seas depends on the pace of the spread of mining activities and the spatial scale of mining impacts in midwaters, both currently unknown: it is likely that commercial DSM in areas beyond national jurisdiction would start slowly and expand whilst an increase in the spatial scale of mining impacts could increase the potential intersection of the two industries considerably.[87] With marine species ranges expected to shift in response to climate change, this could increase the intersection between DSM and fisheries in future.[48] Recent studies show the potential for midwater sediment plumes from discharge water to travel vast distances[54], with a range of impacts for pelagic communities and potential consequences for the fishing industry if target species are affected.[8,87]

A number of emerging changes that are likely to have significant impacts on functioning and conservation of marine biodiversity over the next 5-10 years have been identified.[89] Among these, interest in harvesting largely unexploited mesopelagic fish that live at 200 – 1,000 metres depths has been identified for possible use as fishmeal in aquaculture or in fertilisers.[89] The daily vertical movement of this potentially 10 billion ton community between deep and surface waters transports carbon to the deep sea and contributes to the biological pump. Large-scale removal could disrupt a major pathway of carbon transport into the ocean depths.[89] It is plausible that effects may interact with impacts from mining where they intersect.

Interest in the extraction of lithium from deep-sea brine pools and cold seeps is also highlighted[89], with new technologies, such as solid-state electrolyte membranes increasing the energy efficiency and profitability of lithium extraction from the sea. If permitted to go ahead, DSM opens the way for a range of other seabed resource extraction industries. Other emerging challenges relevant to DSM include increasing pollution from battery production, recycling and disposal that could substantially increase the potentially toxic trace-element contamination in the ocean, and advances in soft robotics for marine research which could enable monitoring and mapping of the deep sea but also add pollutants and waste. [89]

Risks are compounded by governance and regulatory issues and uncertainties

Ocean governance remains fragmented, comprising a patchwork of global and regional instruments and bodies that are often siloed by jurisdiction and human activity, limiting ineffectiveness.[1,19] This will continue to challenge management of the cumulative effects of human activities and climate change in the deep sea.[1] The UN Convention on the Law of the Sea dictates that the High Seas, including the seabed are "the common heritage of mankind" and need to be governed, managed and maintain for the benefit of all mankind. However, the separation of powers pertaining to The Area[xvi] and the High Seas[xvii] has proven particularly problematic[90] given the highly connected nature of the marine environment and the interaction of human activities and their impacts across the seabed and through the water column. Ongoing governance and regulatory uncertainties also make it more difficult to predict the scale of impacts from DSM.[56]

Newly published research further highlights a range of issues in the frameworks, systems and current practices that do not represent a comprehensive, transparent or participative environmental management process.[91,92] The dual mandate of the ISA to protect the Area from serious harm for the benefit of (hu)mankind whilst simultaneously enabling and promoting resource extraction, coupled with the fact that revenues from issuing mining

---

[xvi] Applicable to the seabed, ocean floor and subsoil thereof including its mineral resources beyond national jurisdiction.
[xvii] Applicable to the water column, beyond national jurisdiction.

contracts will fund it creates clear conflicts of interest.[4,93] Concerns have also been raised about opaque decision-making processes and inadequate capacity and lack of environmental expertise within the ISA's advisory body – the Legal and Technical Commission.[4,6] In combination, such governance issues leave the deep sea in a perilous situation.

CAN THE RISKS AND IMPACTS FROM DSM BE EFFECTIVELY PREVENTED, MITIGATED AND MANAGED?

Key points:

The mitigation hierarchy is a framework designed to help users limit, as far as possible, the negative impacts of development projects on biodiversity and ecosystem services. It involves a sequence of four key actions—'avoid', 'minimise', 'restore' and 'offset'—and provides a best practice approach to aid in the sustainable management of living, natural resources by establishing a mechanism to balance conservation needs with development priorities.[94] The mitigation hierarchy is typically applied to achieve no net loss[xviii] or net positive[xix] outcomes.

Fauna & Flora's 2020 assessment emphasised that the full mitigation hierarchy is unachievable in the deep ocean and concluded that the impacts of DSM cannot currently be effectively avoided, mitigated or managed; findings that continue to be reinforced.[19,35] Likewise, ecosystem recovery through passive or assisted restoration remains infeasible and unproven at the current time.

Alongside a growing evidence base showing the potential for the impacts of mining to extend over vast areas and to be both severe and long-lasting, there is insufficient scientific evidence to enable effective mitigation and management of mining impacts on the deep seabed and pelagic ecosystems. Only 1.1% of scientific categories recently assessed across regions with exploratory DSM licenses had enough scientific knowledge to enable evidence-based management.[7,36]

Blanchard and Gollner (2022) emphasise that "*uncertainties and knowledge gaps, both in science and in law, raise concerns as to our ability to ensure comprehensive environmental protection of deep-seabed ecosystems*"[19] whilst the UN Environment Programme Finance Initiative (2022) reinforce that "*at present no robust precautionary approach exists to safeguard the ocean against the potential ecological impacts of DSM.*"[5]

Questions continue to be raised over the effectiveness and appropriateness of existing measures to support impact avoidance in regions targeted for mining.

Preventing impacts is the only way to achieve no harm

With growing recognition of the importance of the deep ocean in providing essential services for humankind and our responsibility to protect it for the benefit of all, it is essential to understand to what extent the anticipated impacts from DSM can be prevented, mitigated and managed such that there is not serious harm to deep-sea ecosystems and the functions and services they provide.

Avoidance of impacts, as emphasised in Fauna & Flora's 2020 assessment, is the only way to achieve no harm or no net loss outcomes as impacts are currently immitigable in time and space. A precautionary approach must be adopted to fulfil the ISA's obligation under the UN Convention on the Law of the Sea to prevent 'serious harm' and ensure the 'effective protection of the marine environment from harmful effects'.

If DSM is permitted to go ahead, it will not be possible to avoid harm given the destructive nature of mining, which will heavily impact the immediate mining area and extend to connected

[xviii] A target of 'no net loss' for biodiversity aims to counterbalance adverse impacts of a development project or programme by positive actions that avoid and minimise, then restore and if necessary, offset biodiversity such that there is no overall reduction in the type, amount or condition of biodiversity. It implies a legacy of no overall harm compared to what would have occurred in the project's absence.

[xix] A net positive outcome for biodiversity is achieved when there is a positive impact on biodiversity that not only balances but exceeds losses caused by development impacts.

benthic and pelagic ecosystems beyond the mine footprint. Some impacts might be partially avoided and/or minimised at a project level, for example, by reducing the footprint of mining within a contracted area, by leaving some minerals with associated fauna in place and undisturbed, or by delivering rejected mining material below 1,500 - 2,000 metres or at the seabed to minimise risks to human seafood supply and other ecosystem services provided by midwater ecosystems. However, options with the least impact are yet to be determined, will likely be region- and resource-specific[8] and may be compromised by the combined effects of mining impacts (e.g., sediment plumes smothering avoided nodule areas).

Technological innovations remain possible in future. For example, Impossible Metals (formerly Impossible Mining) state they are developing an autonomous underwater vehicle that utilises an alternative to dredging technology, such that the autonomous underwater vehicle is designed to hover over the seabed (rather than tracking through sediment) using a dynamic buoyancy system whilst selectively harvesting nodules using a robotic arm.[xx,xxi] The company claims it will avoid contact with the seafloor, avoid '*significant*' sediment plumes whilst an AI driven system that utilises remote sensing technology will detect and avoid nodules hosting deep-sea fauna and be programmed to leave a percentage of nodules as habitat corridors. The company aims for large-scale deployment of this new technology by 2026. However, the need to require the development of best available technology that delivers against stringent objectives-led standards and regulations is crucial. The bar must be set high and incentivise such technological innovation rather than developing standards and regulations to facilitate the development of an industry using available mining technology regardless of the costs to the planet.

The implications of these and other technological advances for deep-sea ecosystems remain unproven with Impossible Metals' trials to date limited to 25 metres depth. Moreover, whilst such technology could play an important role in reducing certain impacts, nodules will still be removed along with their associated microbial communities and meiofauna (a group of benthic animals typically between 0.4 - 1 millimetre in size that live on the seafloor) with implications for deep-sea biodiversity and regulatory functions.

The ISA has developed tools for spatial management in areas targeted for DSM: areas of particular environmental interest (APEIs) which have a conservation objective and within which mining is not permitted; impact reference zones (IRZs); and preservation reference zones (PRZs), intended for monitoring purposes. PRZs are the control zones and designed to be comparable to the IRZ in all respects except for the impact of the activities. To fit within contractor areas, PRZs are expected to be within 100 to 300 km of mining sites[19,58] but they must be large enough and far enough from mining sites to not be affected by mining impacts, including sediment plumes and noise. The approach used for allocating and assessing IRZ and PRZ zones will affect what impacts can be measured, taken into account and managed.[63] How such references zones are designed and designated by contractors is yet to be standardised.[19]

APEIs have only been established for polymetallic nodules in the CCZ, through the Regional Environmental Management Plan (a non-binding policy instrument) that was adopted in 2012. So far, 12 APEIs have been designated. Originally nine (each 400 x 400 km comprising a core 200 x 200 km area and 100 km buffer) were selected to support protection of representative habitats but were relocated to accommodate exploration contract areas in the main manganese nodule belt where nodule densities are highest. In 2021, four additional APEIs outside contracted areas (one notably smaller and without a buffer zone) were adopted by the ISA Council.

[xx] https://uk.news.yahoo.com/eureka-impossible-metals-reveals-successful-120000023.html
[xxi] https://newatlas.com/marine/seabed-mining-robot-impossible-metals/

By relocating APEIs to accommodate nodule mining, APEIs typically have lower nodule densities and different size nodules than the exploration areas, are not representative of future mine sites and have limited similarity to the nearest contract areas.[12,15,63,95,96] This may limit their potential in facilitating ecosystem recovery post-mining, though the potential for nodule-free areas (if unaffected by mining) to protect sediment meiofaunal diversity and as a recruitment source for recolonisation of mined nodule areas has also been noted.[18] Given differences in species occurrence, composition and functions, APEIs may be insufficient as avoidance measures to prevent anticipated loss of fauna and species extinctions. Given uncertainties around the spatial extent of mining impacts, potential for some impacts to extend far beyond the mining footprint (e.g., through plume dispersal[73] or noise[58]), and cumulative effects of mining operations, the 100km buffer zones may prove inadequate in protecting deep-sea species and ecosystems from impacts and supporting post mining recovery.

APEIs are not permanently protected areas and, as sector specific tools, do not offer protection from other human activities beyond mining. It is thus plausible that APEIs might be opened to mining activities in future[90] and be affected by cumulative effects arising from other industries. Issues are compounded by fragmented ocean governance and separation of powers pertaining to the Area and the High Seas, such that the effectiveness of APEIs and other area-based management tools in providing full three-dimensional protection is constrained.[19,97]

Elsewhere, a Regional Environmental Management Plan was recently developed for the northern Mid-Atlantic Ridge (MAR), focussed on polymetallic sulphide deposits for which three exploration contracts have been issued. Three types of area-based management measures are presented in this: areas in need of protection (AINP) and sites in need of protection (SINP) (3 AINPs and 11 SINPS identified), as well as sites and areas in need of precaution (12 identified).[19] However, many questions remain, including the extent to which network criteria such as representativity and connectivity might be incorporated, what differentiates an AINP (as applied in the northern MAR) from an APEI (as applied in the CCZ) and with what implications, and the relationships between the different area-based designations.[19,90] Research demonstrating the significance of chemosynthetic ecosystems for a three-dimensional transition zone around hydrothermal vents has implications for management measures to protect active vents and dependent ecosystems.[19,32] **Blanchard & Gollner**[19] **conclude that in the context of polymetallic sulphides at or near hydrothermal vents "*all current management measures of the ISA would not be suited to protect the marine environment from harmful mining impact*."**

Remediation of impacts is not a viable option

Restoration in the deep sea remains unlikely through any means other than by passive recovery over time for which geological timeframes apply (millions of years). Offsetting is impossible in deep-sea environments. These were the conclusions of Fauna & Flora's assessment in 2020 and they continue to be supported by the evidence, with recovery expected to be further slowed given the latest understanding of the effects of sediment plumes and climate change.

Currently very little is known about species and ecosystem resilience across all deep-sea habitats targeted by mining.[7] Resilience in nodule ecosystems is expected to be low. Maintaining an intact upper-reactive sediment layer, in which microbially-activated processes occur, has been shown to be important and thus a key factor constraining the timeframe of geochemical recovery following disturbance[77]; regeneration of this sediment layer could take thousands of years. Ultimately, nodule ecosystems may never recover without nodules as the essential hard substrate.

For polymetallic sulphide communities, so little is known about these systems that recovery times cannot be estimated, with variation expected between sites.[3,7,35] Given the lengthy timescales over which they formed recovery may require similarly long periods of time.[3] Resilience and recovery rates of encrusted seamounts from mining are not known, though limited data from some taxa affected by bottom trawling indicate recovery could take thousands to millions of years and may vary between seamounts.[7]

Options for restoration have been proposed but remain untested. This includes use of artificial substrates, transplantation or seeding of larvae, and artificial eutrophication of the ocean surface. [18,35] However, such assisted regeneration approaches are expected to be complex, technically challenging, expensive and with potential for causing unintended effects. New long term studies to assess feasibility of restoration at sites of polymetallic nodule mining in the CCZ have been established within the framework of the JPIO project 'Mining Impact II', representing the beginning of a 30+ years study.[98]

ALTERNATIVE PATHWAYS

Some proponents of DSM put forward the argument that DSM is necessary to enable a clean-energy future that "will require billions of tons of metals" and state that "if nodule collection is substantially delayed in order to collect [greater scientific] knowledge, terrestrial mining projects would expand to meet growing demand."[74] However, should DSM go ahead it will likely occur in addition to and not in place of terrestrial mining[6,35], and thus not remove the negative effects of mining on land whilst increased minerals supply could drive metal prices down[35] with implications for Environmental, Social and Governance performance.

It is widely acknowledged that the demand for metals including copper, cobalt, nickel and manganese will increase to support the transition to a low-carbon economy. However, global mineral demand projections and the specific material needs of a transition to a low-carbon economy are highly uncertain, influenced by different potential policy choices, human behaviour, investment decisions, innovation, technology pathways and the rate and scale of manufacturing different technologies.[2,56,99] For example, whilst production of electric car batteries and the associated raw materials are expected to increase, battery technology is evolving requiring less raw material to produce the same amount of energy:

> *"From 2020 to 2030, the average amount of lithium required for a kWh of EV battery drops by half (from 0.10 kg/kWh to 0.05 kg/kWh), the amount of cobalt drops by more than three quarters, with battery chemistries moving towards a lower cobalt content (from 0.13 kg/kWh to 0.03 kg/kWh)."(Mathieu & Mattea 2021)* [99]

Demand may further be mitigated through improved recovery rates for electric car batteries coupled with higher recycling targets (e.g. for portable electronics, EV batteries etc.) that reduce dependency on mining.[99] As such, the case for an urgent switch to DSM is far from proven.[6]

New analyses indicate arguments that DSM is needed due to a physical lack of mineral deposits on land are unsubstantiated[2] and that "*lithium, cobalt, nickel are available in sufficient quantities to enable a rapid, worldwide adoption of electric vehicles*" without DSM.[99]

Crucially, according to a report launched in November 2022, the demand for the seven critical raw minerals studied can be reduced by 58% from now to 2050 with new technology, circular economy models and recycling.[100,101]

> *"The green transition does not need deep-seabed mining to drive a low carbon economy. It is clear that there is a path ahead to decarbonise with a much lesser material footprint."(WWF 2022)* [101]

CONCLUSIONS

Since the publication of Fauna & Flora's 2020 assessment, evidence continues to support its conclusions that the impacts of DSM are likely to be "**extensive and irreversible, permanent and immitigable**" with some impacts, notably from noise and sediment plumes, expected to impact biodiversity and ecosystem services over vast areas. The result will be the loss of deep-sea biodiversity, with implications for associated ecosystem functions and services that are essential at local to planetary scales. Once lost, biodiversity will be impossible to restore.[56]

There is compelling evidence that DSM, through disturbance of marine sediment carbon stores and disruption of carbon cycling and storage processes, could contribute to the climate crisis. Though the magnitude of these effects and interactions between the impacts of DSM and climate change are not yet understood.

The predicted consequences and huge uncertainties associated with DSM must not be ignored. DSM is incompatible with the spirit and intent of the Sustainable Blue Economy[5], goals and targets of the Kunming-Montreal Global Biodiversity Framework and global commitments on climate change.

To advance the DSM industry in the face of the huge gaps in basic understanding of life in the deep sea, very high levels of uncertainty, evidence indicating the severe and widespread nature of DSM impacts, and without data transparency and rigorous science-based standards and guidelines in place, would "*represent the start of a large-scale uncontrolled experiment*."[58]

"*There are no known substitutes or replacements for ecosystem services, such as climate regulation, that operate over large distances and long timescales*"[36] as in the deep sea, and few options to mitigate the effects of climate change on deep-sea ecosystems.[48] It is therefore imperative that we act with the utmost precaution to safeguard the deep ocean and the life-supporting benefits it provides for humanity.[36,56]

We need to acknowledge that the oceans are complex, that we would be unable to mitigate impacts in such a vast and interconnected system and that the precautionary principle is needed in this case. We must protect the long-term stability of planetary processes inherent in the living genesis of metal-rich occurrences in our oceans.

The new science and analyses published since Fauna & Flora's 2020 assessment strongly accentuates the potential risks of DSM. **On the basis of its review, Fauna & Flora concludes that it remains premature for DSM to proceed at the current time.** In the continued absence of any suitable, proven impact-avoidance or mitigation techniques, DSM should be avoided entirely or until such a time as sufficient and robust scientific evidence is available to enable informed, science-based decisions as to whether DSM could be permitted without significant harm to the marine environment and, if so, under what conditions.

There remains an opportunity for a precautionary response, through which the deep-sea ecosystems and potential mining impacts can be comprehensively studied before any decisions are taken to move from DSM exploration to extraction of deep-seabed resources. Bold decisions are required that put ocean health and the benefits of the deep sea for all humankind front and centre because, once initiated, DSM and its effects may be impossible to stop.

REFERENCES

1. Gjerde, K. M. *et al.* Getting beyond yes: fast-tracking implementation of the United Nations agreement for marine biodiversity beyond national jurisdiction. *npj Ocean Sustain.* **1**, (2022).
2. Lusty, P. A. J. *et al. Deep-sea mining evidence review*. (2022). British Geological Society Commissioned Report, CR/21/119. 463pp. Report produced by the British Geological Survey, National Oceanography Centre and Herit-Watt University under contract to FCDO.
3. Smith, C. R. *et al.* Deep-Sea Misconceptions Cause Underestimation of Seabed-Mining Impacts. *Trends Ecol. Evol.* **35**, 853–857 (2020).
4. DSCC. *Deep-sea mining: is the International Seabed Authority fit for purpose?* (2022).
5. United Nations Environment Programme Finance Initiative. *Harmful Marine Extractives: Understanding the risks & impacts of financing non-renewable extractive industries. Deep-sea mining.* (2022).
6. Blue Marine Foundation. *In clear sight. Shining a light on the opaque deep-sea mining industry*. (2020).
7. Amon, D. J. *et al.* Assessment of scientific gaps related to the effective environmental management of deep-seabed mining. *Mar. Policy* **138**, (2022).
8. Drazen, J. C. *et al.* Midwater ecosystems must be considered when evaluating environmental risks of deep-sea mining. *Proc. Natl. Acad. Sci. U. S. A.* **117**, 17455–17460 (2020).
9. Cordier, T. *et al.* Patterns of eukaryotic diversity from the surface to the deep-ocean sediment. *Sci. Adv.* **8**, 26–28 (2022).
10. Thaler, A. D. & Amon, D. 262 Voyages Beneath the Sea: A global assessment of macro- and megafaunal biodiversity and research effort at deep-sea hydrothermal vents. *PeerJ* **7**, 1–27 (2019).
11. Ingels, J. *et al.* Ecological variables for deep-ocean monitoring must include microbiota and meiofauna for effective conservation. *Nat. Ecol. Evol.* **5**, 27–29 (2021).
12. Christodoulou, M. *et al. Unexpected high abyssal ophiuroid diversity in polymetallic nodule fields of the northeast Pacific Ocean and implications for conservation*. *Biogeosciences* **17**, (2020).
13. Bribiesca-Contreras, G. *et al.* Benthic megafauna of the western Clarion-Clipperton Zone, Pacific Ocean. *Zookeys* **1113**, 1–110 (2022).
14. Sánchez, N. *et al.* Diversity and distribution of Kinorhyncha in abyssal polymetallic nodule areas of the Clarion-Clipperton Fracture Zone and the Peru Basin, East Pacific Ocean, with the description of three new species and notes on their intraspecific variation. *Mar. Biodivers.* **52**, (2022).
15. Bonifácio, P., Martínez Arbizu, P. & Menot, L. Alpha and beta diversity patterns of polychaete assemblages across the nodule province of the eastern Clarion-Clipperton Fracture Zone (equatorial Pacific). *Biogeosciences* **17**, 865–886 (2020).
16. Washburn, T. W. *et al.* Patterns of macrofaunal biodiversity across the Clarion-Clipperton Zone: an area targeted for seabed mining. *Front. Mar. Sci.* **8**, 1–22 (2021).
17. Brix, S. *et al.* Adult life strategy affects distribution patterns in abyssal isopods - implications for conservation in Pacific nodule areas. *Biogeosciences* **17**, 6163–6184 (2020).
18. Pape, E. *et al.* Potential impacts of polymetallic nodule removal on deep-sea meiofauna. *Sci. Rep.* **11**, 1–15 (2021).
19. Blanchard, C. & Gollner, S. Area-based management tools to protect unique hydrothermal vents from harmful e ects from deep-sea mining : A review of ongoing developments. *Front. Polit. Sci.* **4: 1033251**, (2022).
20. Mohrbeck, I., Horton, T., Jażdżewska, A. M. & Martínez Arbizu, P. DNA barcoding and cryptic diversity of deep-sea scavenging amphipods in the Clarion-Clipperton Zone (Eastern Equatorial Pacific). *Mar. Biodivers.* **51**, (2021).
21. Lejzerowicz, F. *et al.* Eukaryotic biodiversity and spatial patterns in the Clarion-Clipperton Zone and other abyssal regions: insights from sediment DNA and RNA metabarcoding. *Front. Mar. Sci.* **8**, 1–23 (2021).
22. Van Dover, C. L. *et al.* Research is needed to inform environmental management of hydrothermally inactive and extinct polymetallic sulfide (PMS) deposits. *Mar. Policy* **121**, 104183 (2020).
23. Molari, M., Janssen, F., Vonnahme, T. R., Wenzhöfer, F. & Boetius, A. The contribution of microbial communities in polymetallic nodules to the diversity of the deep-sea microbiome of the Peru Basin (4130-4198m depth). *Biogeosciences* **17**, 3203–3222 (2020).
24. de Jonge, D. S. W. *et al.* Abyssal food-web model indicates faunal carbon flow recovery and impaired microbial loop 26 years after a sediment disturbance experiment. *Prog. Oceanogr.* **189**, (2020).
25. Andrianov, B. A. Probable microbiological origin of chemical elements in polymetallic nodules on the ocean floor. *Infin. Energy* 24–28 (2020).
26. Orcutt, B. N. *et al.* Impacts of deep-sea mining on microbial ecosystem services. *Limnol. Oceanogr.* **65**, 1489–1510 (2020).
27. Klunder, L. *et al.* A molecular approach to explore the background benthic fauna around a hydrothermal vent and their larvae: implications for future mining of seep-sea SMS deposits. *Front. Mar. Sci.* **7**, 1–12 (2020).
28. Chen, C., Lin, T. H., Watanabe, H. K., Akamatsu, T. & Kawagucci, S. Baseline soundscapes of deep-sea habitats reveal heterogeneity among ecosystems and sensitivity to anthropogenic impacts. *Limnol. Oceanogr.* **66**, 3714–3727 (2021).
29. Stratmann, T., Soetaert, K., Kersken, D. & van Oevelen, D. Polymetallic nodules are essential for food-web integrity of a prospective deep-seabed mining area in Pacific abyssal plains. *Sci. Rep.* **11**, (2021).
30. De Smet, B. *et al.* The megafauna community from an abyssal area of interest for mining of polymetallic

nodules. *Deep. Res. Part I Oceanogr. Res. Pap.* **172**, (2021).
31. Ashford, O. S. *et al.* Relationships between biodiversity and ecosystem functioning proxies strengthen when approaching chemosynthetic deep-sea methane seeps. *Proc. R. Soc. B Biol. Sci.* **288**, (2021).
32. Cordes, E. *et al. Redefining the influence of chemosynthetic ecosystems for effective management*. Deep Ocean Stewardship Initiative (DOSI) Policy Brief (2021). www.dosi-project.org/wp-content/uploads/Chemosynthetic-Ecosystems-Policy-Brief.pdf
33. Åström, E. K. L., Bluhm, B. A. & Rasmussen, T. L. Chemosynthetic and photosynthetic trophic support from cold seeps in Arctic benthic communities. *Front. Mar. Sci.* **9**, 1–19 (2022).
34. Roohi, R. *et al.* Influence of Chemoautotrophic Organic Carbon on Sediment and Its Infauna in the Vicinity of the Rainbow Vent Field. *Front. Mar. Sci.* **9**, 1–11 (2022).
35. Levin, L. A., Amon, D. J. & Lily, H. Challenges to the sustainability of deep-seabed mining. *Nat. Sustain.* **3**, 784–794 (2020).
36. Amon, D., Levin, L. & Andersen, N. *Undisturbed: The deep ocean's vital role in safeguarding us from crisis*. (2022). http://www.stateoftheocean.org/wp-content/uploads/2022/11/DeepSea-Synthesis-31oct-high.pdf
37. Laffoley, D. *et al.* The forgotten ocean: Why COP26 must call for vastly greater ambition and urgency to address ocean change. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **32**, 217–228 (2021).
38. Trenberth, K. Understanding climate change through Earth's energy flows. *J. R. Soc. New Zeal.* **50**, 331–347 (2020).
39. Bianchi, T. S. *et al.* What global biogeochemical consequences will marine animal-sediment interactions have during climate change? *Elementa* **9**, 1–25 (2021).
40. Atwood, T. B., Witt, A., Mayorga, J., Hammill, E. & Sala, E. Global patterns in marine sediment carbon stocks. *Front. Mar. Sci.* **7**, 1–9 (2020).
41. Hilmi, N. *et al.* The role of blue carbon in climate change mitigation and carbon stock conservation. *Front. Clim.* **3**, (2021).
42. Saba, G. K. *et al.* Toward a better understanding of fish-based contribution to ocean carbon flux. *Limnol. Oceanogr.* **66**, 1639–1664 (2021).
43. Simon-Lledó, E. *et al.* Mass falls of crustacean carcasses link surface waters and the deep seafloor. *Ecology* (2022). doi:doi.org/10.1002/ecy.3898
44. Mariani, G. *et al.* Let more big fish sink: Fisheries prevent blue carbon sequestration-half in unprofitable areas. *Sci. Adv.* **6**, 1–9 (2020).
45. Cheung, W. W. L., Wei, C. L. & Levin, L. A. Vulnerability of exploited deep-sea demersal species to ocean warming, deoxygenation, and acidification. *Environ. Biol. Fishes* (2022). doi:10.1007/s10641-022-01321-w
46. Georgian, S. *et al.* Scientists' warning of an imperiled ocean. *Biol. Conserv.* **272**, 109595 (2022).
47. Sweetman, A. K. *et al.* Major impacts of climate change on deep-sea benthic ecosystems. *Elementa* **5**, (2017).
48. Levin, L. A. *et al.* Climate change considerations are fundamental to management of deep-sea resource extraction. *Glob. Chang. Biol.* **26**, 4664–4678 (2020).
49. Levin, L. A. IPCC and the deep sea: a case for deeper knowledge. *Front. Clim.* **3**, 2020–2022 (2021).
50. Brito-Morales, I. *et al.* Climate velocity reveals increasing exposure of deep-ocean biodiversity to future warming. *Nat. Clim. Chang.* **10**, 576–581 (2020).
51. Loarie, S. R. *et al.* The velocity of climate change. *Nature* **462**, 1052–1055 (2009).
52. Danovaro, R. *et al.* Ecological variables for developing a global deep-ocean monitoring and conservation strategy. *Nat. Ecol. Evol.* **4**, 30–31 (2020).
53. Christiansen, S., Bräger, S. & Jaeckel, A. Evaluating the quality of environmental baselines for deep seabed mining. *Front. Mar. Sci.* **9**, (2022).
54. Muñoz-Royo, C. *et al.* Extent of impact of deep-sea nodule mining midwater plumes is influenced by sediment loading, turbulence and thresholds. *Commun. Earth Environ.* **2**, 1–16 (2021).
55. Amon, D. J., Levin, L. A., Metaxas, A., Mudd, G. M. & Smith, C. R. Heading to the deep end without knowing how to swim: Do we need deep-seabed mining? *One Earth* **5**, 220–223 (2022).
56. Miller, K. A. *et al.* Challenging the Need for Deep Seabed Mining From the Perspective of Metal Demand, Biodiversity, Ecosystems Services, and Benefit Sharing. *Front. Mar. Sci.* **8**, (2021).
57. OSPAR Commission. *OSPAR technical report on current understanding of deep seabed mining resources, technology, potential impacts and regulation along with the current global demand for minerals*. (2021). https://www.ospar.org/documents?v=46926
58. Williams, R. *et al.* Noise from deep-sea mining may span vast ocean areas. Potential harm is understudied and largely overlooked. *Science.* **377**, 8–10 (2022).
59. Ouillon, R., Muñoz-Royo, C., Alford, M. H. & Peacock, T. Advection-diffusion-settling of deep-sea mining sediment plumes. Part 1: Midwater plumes. *Flow* **2**, (2022).
60. Gillard, B., Harbour, R. P., Nowald, N., Thomsen, L. & Iversen, M. H. Vertical distribution of particulate matter in the Clarion Clipperton Zone (German Sector)—Potential impacts from deep-sea mining discharge in the water column. *Front. Mar. Sci.* **9**, (2022).
61. Muñoz-Royo, C. *et al.* Extent of impact of deep-sea nodule mining midwater plumes is influenced by sediment loading, turbulence and thresholds. *Commun. Earth Environ.* **2**, 1–16 (2021).
62. Ou, R. *et al.* Simulation experiment of environmental impact of deep-sea mining: response of phytoplankton community to polymetallic nodules and sediment enrichment in surface water. *Toxics* **10**,

(2022).
63. Jones, D. O. B., Ardron, J. A., Colaço, A. & Durden, J. M. Environmental considerations for impact and preservation reference zones for deep-sea polymetallic nodule mining. *Mar. Policy* **118**, 103312 (2020).
64. Ouillon, R., Muñoz-Royo, C., Alford, M. H. & Peacock, T. Advection–diffusion settling of deep-sea mining sediment plumes. Part 2. Collector plumes. *Flow* **2**, (2022).
65. Shi, P., Yang, J., Sun, D. & Wang, C. A simulation from offsite disturbance experiments on the metal resuspension process in the seafloor of the Western Pacific. *Chemosphere* **311**, 137042 (2023).
66. van der Grient, J. M. A. & Drazen, J. C. Evaluating deep-sea communities' susceptibility to mining plumes using shallow-water data. *Sci. Total Environ.* **852**, 158162 (2022).
67. Baeye, M. *et al.* Tidally driven dispersion of a deep-sea sediment plume originating from seafloor disturbance in the discol area (Se-pacific ocean). *Geosci.* **12**, (2022).
68. Kim, M. G., Hyeong, K., Yoo, C. M., Lee, J. Y. & Seo, I. Characterization of fines produced by degradation of polymetallic nodules from the clarion–clipperton zone. *Minerals* **11**, 1–14 (2021).
69. Spearman, J. *et al.* Measurement and modelling of deep sea sediment plumes and implications for deep sea mining. *Sci. Rep.* **10**, 1–14 (2020).
70. Morato, T. *et al.* Modelling the dispersion of seafloor massive sulphide mining plumes in the Mid Atlantic Ridge around the Azores. *Front. Mar. Sci.* **9**, 1–18 (2022).
71. Carreiro-Silva, M. *et al.* Mechanical and toxicological effects of deep-sea mining sediment plumes on a habitat-forming cold-water octocoral. *Front. Mar. Sci.* **9**, 1–23 (2022).
72. Martins, I., Godinho, A., Rakka, M. & Carreiro-Silva, M. Beyond deep-sea mining sublethal effects: Delayed mortality from acute Cu exposure of the cold-water octocoral Viminella flagellum. *Mar. Pollut. Bull.* **183**, (2022).
73. Weaver, P. P. E. *et al.* Assessing plume impacts caused by polymetallic nodule mining vehicles. *Mar. Policy* **139**, 105011 (2022).
74. Paulikas, D., Katona, S., Ilves, E. & Ali, S. H. Deep-sea nodules versus land ores: A comparative systems analysis of mining and processing wastes for battery-metal supply chains. *J. Ind. Ecol.* 1–24 (2022). doi:10.1111/jiec.13225
75. Vonnahme, T. R. *et al.* Effects of a deep-sea mining experiment on seafloor microbial communities and functions after 26 years. *Sci. Adv.* **6**, (2020).
76. Boehringer, L. *et al.* Recovery of Paleodictyon patterns after simulated mining activity on Pacific nodule fields. *Mar. Biodivers.* **51**, 1–12 (2021).
77. Haffert, L., Haeckel, M., De Stigter, H. & Janssen, F. Assessing the temporal scale of deep-sea mining impacts on sediment biogeochemistry. *Biogeosciences* **17**, 2767–2789 (2020).
78. Heinrich, L., Koschinsky, A., Markus, T. & Singh, P. Quantifying the fuel consumption, greenhouse gas emissions and air pollution of a potential commercial manganese nodule mining operation. *Mar. Policy* **114**, 103678 (2020).
79. Sala, E. *et al.* Protecting the global ocean for biodiversity, food and climate. *Nature* **592**, 397–402 (2021).
80. Paulikas, D., Katona, S., Ilves, E. & Ali, S. H. Life cycle climate change impacts of producing battery metals from land ores versus deep-sea polymetallic nodules. *J. Clean. Prod.* **275**, 123822 (2020).
81. Katona, S., Paulikas, D. & Stone, G. S. Ethical opportunities in deep-sea collection of polymetallic nodules from the Clarion-Clipperton Zone. *Integr. Environ. Assess. Manag.* **18**, 634–654 (2022).
82. Alvarenga, R. A. F., Préat, N., Duhayon, C. & Dewulf, J. Prospective life cycle assessment of metal commodities obtained from deep-sea polymetallic nodules. *J. Clean. Prod.* **330**, (2022).
83. Ackerman, D. Deep-Sea Mining: How to Balance Need for Metals with Ecological Impacts As the industry inches closer to reality, scientists probe potential environmental harms. *Scientific American* (2020).
84. Carver, R. *et al.* A critical social perspective on deep sea mining: Lessons from the emergent industry in Japan. *Ocean Coast. Manag.* **193**, 105242 (2020).
85. Hamley, G. J. The implications of seabed mining in the Area for the human right to health. *Rev. Eur. Comp. Int. Environ. Law* 1–10 (2022). doi:10.1111/reel.12471
86. Thiele, T., Damian, H.-P. & Singh, P. A Comprehensive Approach to the Payment Mechanism for Deep Seabed Mining. *IASS Policy Br.* 1–16 (2021). doi:10.48440/iass.2021.004
87. van der Grient, J. M. A. & Drazen, J. C. Potential spatial intersection between high-seas fisheries and deep-sea mining in international waters. *Mar. Policy* **129**, 104564 (2021).
88. iAtlantic. *Scale and nature of impacts from mining seafloor polymetallic sulphide deposits. Summary of latest research from the iAtlantic project.* (2022).
89. Herbert-Read, J. E. *et al.* A global horizon scan of issues impacting marine and coastal biodiversity conservation. *Nat. Ecol. Evol.* **6**, 1262–1270 (2022).
90. Christiansen, S., Durussel, C., Guilhon, M., Singh, P. & Unger, S. Towards an ecosystem approach to management in Areas Beyond National Jurisdiction: REMPs for deep seabed mining and the proposed BBNJ Instrument. *Front. Mar. Sci.* **9**, 1–23 (2022).
91. Komaki, K. & Fluharty, D. Options to improve transparency of environmental monitoring governance for polymetallic nodule mining in the Area. *Front. Mar. Sci.* **7**, (2020).
92. Guilhon, M., Singh, P., Christiansen, S. & Turra, A. Revisiting procedural requirements for the assessment of environmental impacts arising from the different stages of deep seabed mining: Current practices at the International Seabed Authority and recommendations for improvement. *Environ. Impact Assess. Rev.* **96**, 106846 (2022).
93. House of Commons Environmental Audit Committee. *Sustainable Seas, Fourteenth Report of Session*

2017–19. Report, together with formal minutes relating to the report. (2019). https://publications.parliament.uk/pa/cm201719/cmselect/cmenvaud/980/980.pdf
94. CSBI. *A cross-sector guide for implementing the mitigation hierarchy*. Prepared by the Biodiversity Consultancy on behalf of IPIECA, ICMM and the Equator Principles Association. (2015). http://www.csbi.org.uk/our-work/mitigation-hierarchy-guide/
95. Washburn, T. W., Jones, D. O. B., Wei, C. L. & Smith, C. R. Environmental heterogeneity throughout the Clarion-Clipperton Zone and the potential representativity of the APEI network. *Front. Mar. Sci.* **8**, 1–17 (2021).
96. McQuaid, K. A. *et al.* Using habitat classification to assess representativity of a protected area network in a large, data-poor area targeted for deep-sea mining. *Front. Mar. Sci.* **7**, 1–21 (2020).
97. Blanchard, C., Harrould-Kolieb, E., Jones, E. & Taylor, M. L. The current status of deep-sea mining governance at the International Seabed Authority. *Mar. Policy* **147**, 105396 (2023).
98. Gollner, S. *et al.* Restoration experiments in polymetallic nodule areas. *Integr. Environ. Assess. Manag.* **18**, 682–696 (2022).
99. Mathieu, L. & Mattea, C. *From dirty oil to clean batteries*. European Federation for Transport and Environment AISBL. (2021).
100. Simas, M., Aponte, F. & Wiebe, K. *The future is circular. Circular economy and critical minerals for the green transition*. Report prepared by SINTEF for WWF (2022).
101. WWF. *The future is circular: The circular economy and critical minerals for the green transition. WWF summary and recommendations for policy makers*. (2022). https://wwfint.awsassets.panda.org/downloads/circular_economy_and_critical_minerals_report_summary_and_recommendations_1.pdf

If you have any questions or would like more information, please contact:

Sophie Benbow
Director, Marine

Catherine Weller
Director, Global Policy

FAUNA & FLORA INTERNATIONAL

Registered Charity No. 1011102

The David Attenborough Building,
Pembroke Street, Cambridge,
CB2 3QZ, United Kingdom

Tel: +44 (0) 1223 571 000
Email: info@fauna-flora.org
www.fauna-flora.org