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Developing best environmental practice for polymetallic nodule mining - a review of scientific recommendations

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Best environmental practice (BEP) is a key component of an ecosystem approach to management and is typically a product of practical experience in established industries. For an emerging activity such as deep seabed mining, no such experience will exist at the time of deciding on the permissibility of the first industrial mines. Therefore, experience from deep ocean scientific experiments and research are important to develop a preliminary understanding of BEP for deep seabed mining. This paper offers a detailed review of the scientific literature from which it identifies elements of preliminary BEP for nodule mining. The paper describes the currently envisaged mining process for manganese nodules and its expected effects on the environment and extracts specific recommendations on how to minimise environmental impacts from mining in different layers of the ocean (benthic, benthopelagic, pelagic, and surface waters) as well as from noise and light impacts. In doing so, the paper aims to inform the Mining Code being developed by the International Seabed Authority (ISA). The ISA is the intergovernmental institution mandated to organise and control seabed mining on the international seabed. The ISA is obligated to ensure effective protection of the marine environment from harm likely to arise from mining, with BEP being a core tool to achieve that. This paper provides suggestions for a future ISA Standard on BEP.

KEYWORDS

best environmental practice, deep seabed mining, environment, governance, polymetallic (manganese) nodules

1 Introduction

Deep seabed mining (DSM) is an emerging industry that could carry significant risks for the marine environment. Mining operations will cause biodiversity loss (Van Dover et al., 2017; Niner et al., 2018) and knock-on effects on the food web (Stratmann et al., 2018; Stratmann et al., 2021) due to habitat destruction (Vanreusel et al., 2016; Volz et al., 2020), sediment plumes (Muñoz-Royo et al., 2022) and noise and light pollution (Williams et al., 2022). In aiming to reduce those environmental risks through an ecosystem-based and precautionary approach (ITLOS, 2011), the International Seabed Authority (ISA), which regulates and manages all DSM-related activities on the international seabed "Area",[1] requires mining operators to apply Best Environmental Practice (BEP).[2] In this context, BEP means 'the most appropriate combination of environmental control measures and strategies' at any given point in time.[3] BEP, by definition, improves over time depending on upcoming environmental challenges as well as advances in knowledge and technology, including Traditional Knowledge by Indigenous Peoples and local communities.[4]

Identifying BEP is never an easy task but may be particularly difficult for an emerging industry that does not yet have a proven track record of safe operations and that uses nascent technologies which are largely untested in the deep ocean environment. Because of these challenges, identifying BEP for DSM will initially have to rely on experience from other offshore industries as well as on long-term experience gained from small-scale scientific disturbance experiments and mining tests. To that effect, this paper seeks to identify elements of preliminary BEP for polymetallic nodule mining, based on a review of scientific recommendations from the literature. This can only be a first approximation, as a multitude of additional, in particular experimental process research (Weaver et al., 2022) and extended test mining with full-size equipment will be necessary to provide knowledge on short- and long-term environmental effects of DSM from *in situ* operational practices (Amon et al., 2022; Singh and Christiansen, 2022; Weaver et al., 2022).

Identifying BEP is important for at least three actors: the ISA as the regulator, the mining companies, States or State enterprises as contractors, and the sponsoring State of the contractor. The ISA is obligated to ensure effective protection of the marine environment from harmful effects of DSM,[5] with BEP being one important element in achieving this obligation, as specifically recognized in the draft regulations for mineral exploitation which the ISA is currently developing.[6] Identifying BEP prior to the start of commercial mining is key to enable the ISA to assess whether an applicant has indeed been following BEP. The applicant, in turn, needs to demonstrate that its proposed plan for mineral exploration[7] or exploitation[8] applies BEP as well as best available techniques (BAT).[9] Lastly, the sponsoring State is required to apply BEP both as a direct obligation[10] and as part of its due diligence obligation to ensure that the contractor complies with its obligations.[11] Clarity on what constitutes BEP at any given point in time is thus fundamental for the ISA, its contractors, and sponsoring States to be able to comply with their respective obligations.

Despite the importance of BEP, there is no agreed understanding on what constitutes BEP in the Area. Indeed, in the absence of respective environmental standards, the ISA's current approach entrusts individual ISA contractors with identifying project-specific and area-specific impact thresholds[12] to determine BEP and other standards based on their baseline data collection. These may be guided by (non-binding) guidelines issued by the ISA (Brown, 2018). However, a common understanding of current BEP, and its links to good industry practice and best available technology,[13] may be essential to articulate ISA standards, and to help contractors optimize their technology to meet those standards, while reducing financial and legal risks for contractors. Lastly, BEP may help the ISA to assess and compare applications for mineral exploration or exploitation.

Indeed, in 2017, the Netherlands proposed for the ISA Council to develop an assessment and approval methodology to evaluate mining equipment, operational procedures and processes in

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[1] 1982 UN Convention on the Law of the Sea (UNCLOS), Art 1(1)(1).

[2] See ITLOS, 2011, paras 122 and 136.

[3] ISA, Draft regulations on exploitation of mineral resources in the Area: Parts IV and VI and related Annexes, ISBA/28/C/IWG/ENV/CRP.1, 2 March 2023, Schedule, page 91.

[4] ISA, Draft regulations on exploitation of mineral resources in the Area: Parts IV and VI and related Annexes, ISBA/28/C/IWG/ENV/CRP.1, 2 March 2023, Schedule, page 91.

[5] UNCLOS, Art 145.

[6] See e.g. ISA, Draft regulations on exploitation of mineral resources in the Area: Parts IV and VI and related Annexes, ISBA/28/C/IWG/ENV/CRP.1, 2 March 2023, draft Regulation 44(2 bis)(b), (c).

[7] ISA, Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area, ISBA/19/C/17, 22 July 2013, Regulation 31(5).

[8] ISA, Draft regulations on exploitation of mineral resources in the Area: Parts IV and VI and related Annexes, ISBA/28/C/IWG/ENV/CRP.1, 2 March 2023, draft Regulation 44(2 bis)(b), (c).

[9] E.g. ISA, Draft regulations on exploitation of mineral resources in the Area: Parts IV and VI and related Annexes, ISBA/28/C/IWG/ENV/CRP.1, 2 March 2023, draft Regulation 46bis(1), 46ter(1), 48(3)(c). For a discussion paper on BEP and best available technology, see ISA, Key terms: distinguishing between good industry practice and best practices under the draft regulations on exploitation of mineral resources in the Area, ISBA/25/C/11, 15 January 2019.

[10] See e.g. ISA, Draft regulations on exploitation of mineral resources in the Area: Parts IV and VI and related Annexes, ISBA/28/C/IWG/ENV/CRP.1, 2 March 2023, draft Regulation 44(2 bis)(b), (c); ISA, Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area, ISBA/19/C/17, 22 July 2013, Regulation 31(2).

[11] Seabed Disputes Chamber, Responsibilities and Obligations of States Sponsoring Persons and Entities with Respect to Activities in the Area (Advisory Opinion, case no 17, 2011) para 136.

[12] see ISBA/27/C/4, para 88: 'Until such time as sufficient data on the Area exists to allow the Authority to establish thresholds for a range of key components that are assessed in the EIA process, an applicant or Contractor should use project-specific and area- specific impact thresholds based on data and analyses commensurate in quality with the importance of the impact.'

[13] see e.g. ISBA/25/C/11.

relation to their impact on the marine environment.[14] The proposal was for the ISA to develop technical standards and minimum environmental requirements. Only certified technology would receive approval in prior Environmental Impact Assessments. Certification could be considered early in the technological and operational design process, offering a degree of certainty to mining contractors. In addition, once the criteria exist, the assessment and certification process for equipment could be delegated to external bodies, as is customary for ships and other offshore equipment. Alternatively, an independent advisory body or the future inspection unit of the ISA could fulfil this role.

While no such methodology is being developed yet, the ISA Council has recently decided to take a more active approach and develop environmental thresholds for permissible levels of toxicity, noise, light, and turbidity as well as settling of resuspended sediments from DSM.[15] This will be an important step towards identifying what levels of environmental harm are deemed acceptable, which in turn supports the identification of BEP to meet these thresholds.

This paper starts by outlining the methodology (section 2), followed by a brief overview of potential nodule mining operations (section 3). The paper then addresses the key effects of nodule mining on relevant ocean layers, from the seafloor (section 4), benthic boundary layer (section 5), water column and surface waters (section 6) and noise and light pollution (section 7). Each section discusses the main risks and recommendations for BEP. Section 8 offers overarching recommendations, while section 9 formulates suggestions for a future ISA Standard on BEP, and section 10 offers concluding thoughts.

2 Materials and methods

This paper offers a non-exhaustive list of preliminary recommendations for BEP in nodule mining, expressed as such in relevant scientific publications. The study draws on a broad range of recent studies which provide direct recommendations for managing DSM. Indirect or implied recommendations from the literature were not considered. Overall, the recommendations largely build on each other, although in some cases differences exist, which are reflected in this paper.

We purposefully do not attempt to rank these recommendations in importance, ease of attainability, scales of effects or cost. This will require a broader range of expertise to systematically assess risks and consider all available options for keeping the short- and long-term impacts on of DSM within the limits to be formulated by the ISA in the future. The present paper merely presents a starting point for developing BEP.

3 Overview of potential polymetallic nodule operations

Of the three minerals, the ISA is concerned with since its creation, polymetallic nodules have been studied most extensively. Polymetallic nodules in the Area are generally between 1 and 12 cm in diameter and lie half-buried in the sediment in abundances amounting up to more than 20 kg/m^2 in some parts of the Clarion-Clipperton Fracture Zone, CCZ, in the Eastern Tropical Pacific. In certain biogeographic regions of all oceans, the nodules can occur in contiguous fields of similar-sized nodules interspersed with low abundance regions or areas that are almost devoid of nodules (Kuhn et al., 2020). The metal content of the nodules varies with location, size, formation process and weathering state (Kuhn et al., 2020). Nodule abundance and nodule size affect biological communities directly and indirectly (Vanreusel et al., 2016; Smet et al., 2017; Kuhn et al., 2020; Simon-Lledó et al., 2020).

Harvesting nodules means retrieving them from the seafloor and pumping the collected material to a surface vessel through a vertical riser pipe (Jones et al., 2017; Miller et al., 2018). All proposed seabed mineral mining operations are based on a similar concept, which encompasses four major components: (1) extraction tool, (2) riser system, (3) surface platform, and (4) disposal system. Most proposed seabed collection systems envisage the use of remotely operated vehicles, which would extract the nodules from the seabed using mechanical rakes or pressurized water. Although less invasive collection technologies are in the design phase,[16] the nodule collection techniques that are currently being tested all involve self-propelled heavy machinery (with up to 100 t weight under water) operating on the seafloor, and removing up to 10-50 cm of the upper sediment (e.g. reviewed by Paul et al., 2018). So far, the nodule collectors will either consist of one large machine with one or several hydraulic sucking, or raking (e.g. India) intake units, or of several identical modules (e.g. DEME-GSR), mounted together or operating in isolation (Deepak et al., 2001; Handschuh et al., 2001; GSR, 2018; Government of India, 2020). The type of collector will determine the width of the collector path. The machine(s) will strip-mine in a lawnmower pattern, with software ensuring the continuous clearing of nodules (Volkmann and Lehnen, 2017). In most cases, the maximum terrain angle that can be cleared of nodules is 3-4% (Kuhn et al., 2011), any steeper or rougher terrain will remain inaccessible. These figures have not changed since the early pilot mining tests, when the National Oceanographic and Atmospheric Administration of the USA (NOAA, 1981) calculated that a nodule collector will traverse 1.9 km^2 per day, of which 0.8 km^2 are not mineable.

The future exploitation contracts for minerals in the Area are likely to be valid for a period of three decades.[17] Van Nijen et al.

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[14] ISA, Development of environmentally responsible mining technologies: towards an approval process for mining equipment, ISBA/23/C/5, 1 June 2017.

[15] ISA, Decision of the Council of the International Seabed Authority Relating to the Development of Binding Environmental Threshold Values, ISBA/27/C/42, 11 November 2022.

[16] See e.g. https://impossiblemetals.com/technology/robotic-collection-system/.

(2018) assume a mine life of 25 years. The "BlueMining" nodule mining concept presented by (Volkmann and Lehnen, 2017) assumes an annual production of 1.5-2 Mio t (dry weight, DW) of nodules and expects mining operations to be operational 250 days per year and 20 hours per day. To achieve this production capacity, the nodule collection must reach 400 t DW per hour, and the lifting capacity must achieve 150 kg DW per second. For a mine life of 20 years, the German contractor, BGR, calculates that at a conservative resource abundance of 10 kg of dry material per m^2 would result in the extraction of nodules from 100 and 200 km^2 per year or 2300-3600 km^2 (equivalent to the surface area of Luxemburg) over 20 years (Volkmann and Lehnen, 2017).

However, the total seafloor area impacted by individual mining projects will be much larger than suggested by the above figures, particularly as the mine site will rarely be one contiguous area but rather a patchwork of mineable and non-mineable sites (Kuhn et al., 2020). In case of the French contract area in the CCZ, individual mining blocks are expected to be no larger than 100 km^2 of variable shape (Lenoble, pers com. in Thiel et al., 2005). Estimates for the total area directly impacted by one 20-year mining operation range from to 6500-14,000 km^2 (Volkmann and Lehnen 2017), to 28,000-56,000 km^2 when considering the sediments plumes generated by the collector vehicle (Sharma et al., 2001).[18] The overall benthic footprint of a single mine over 20 years may be at least 2 to 4 times larger than the mined area itself (Smith et al., 2020). The cumulative impact of several mines in a biogeographic subregion, for example in the eastern CCZ, could degrade substantial portions of the approx. 500,000 km^2 nodule habitat in the CCZ (Smith et al., 2020).

The nodules collected are separated from the cohesive sediment, both while entering the collector, and inside the collector. Finally, the sediment slurry – possibly ejected by the collector through an exhaust pipe several meters above the seafloor – creates an operational plume of which the larger particle fraction is likely to resettle on the seafloor, while the fine fraction will drift away and remain in the water column for a long time (Baeye et al., 2021; Purkiani et al., 2021; Muñoz-Royo et al., 2022; Weaver et al., 2022).

The nodules may be crushed to be transported as a slurry up to the surface vessel for dewatering, pre-processing and transport to land. Several technologies are under discussion for lifting the ore slurry to the surface ship (Ma et al., 2017), some of which require underwater pumps (Verichev et al., 2012; Ma et al., 2017) likely to cause vibration and noise pollution. The non-mechanical transport systems (pneumatic or hydraulic lifting) require pipes of several kilometers length where the turbulence will cause nodule degradation through particle fragmentation, chipping, attrition, and/or abrasion (Kim et al., 2021). Particles smaller than 8 µm in diameter will be unlikely to be technically recoverable from the slurry and thus likely to be discharged after pre-processing at sea (Van Wijk and De Hoog, 2020; Kim et al., 2021). As an alternative, Ma et al. (2017) propose a mechanical collection and riser system in open or closed containers, though with a lower production capacity in deep water.

It is yet unclear, whether contractors are aiming at beneficiation of the nodules only, *i.e.*, after dewatering of the nodule slurry for storage, with unrecoverable fractions being discharged at certain depths, or whether a partial treatment of the nodules by chemical and physical means is considered to produce a concentrated intermediate product at sea. A third option would be to carry out the full processing or refining at sea, which seems rather unlikely given the energy requirements.

The ore might have to be watered again for transshipment (inter-ship transfer onto transport barges). This would result in more excess water to be discharged from the transport vessel (likely to surface waters and this time most likely of different physical and chemical composition). A recent publication indicates potential health risks for humans when handling nodule material owing to substantial alpha radiation being emitted from stored and dewatered nodules (Volz et al., 2023).

In addition to vessel-generated noise, the entire mining process from the seafloor to the support vessel will create noise pollution. This includes acoustic telemetry which is employed for positioning, locating, equipment steering and controlling remotely operated vessels (ROV) to support extraction operations. Sound is also used, for example, to communicate with landers, AUVs and other equipment.

An overview of environmental pressures resulting from the excavation process is provided in ISBA/23/C/5, Annex and other reviews (e.g., ICES, 2015; Kaikkonen et al., 2018; Leal Filho et al., 2021, Table 3). In the following, we provide a summary of the currently known likely effects of nodule mining on relevant layers of the ocean, as well as recommendations for BEP from the literature.

4 Seafloor

4.1 Operational effects of collection on the seafloor

Key risks to seafloor integrity result from the removal of the nodules as an essential structural habitat, the destruction of the biogeochemical structure and function of the sediments, and the indirect degradation of adjacent areas through smothering by re-sedimentation, e.g., of operational plumes.

As described above, nodule mining operations target level and soft sediment environments in regions with extremely low sedimentation rates of on average 3.5-5 mm/1000 years in the eastern CCZ (Khripounoff et al., 2006; Mewes et al., 2014; Kuhn et al., 2017). In general, nodule collection will result in the removal of hard substrate, diminished rugosity and qualitative change of large expanses of seafloor for an indefinite time. Effects will be visible from fine-scale to landscape level, e.g. from a vertical removal of the bioactive upper 7 cm of the sediment (Volz et al., 2020), exposing sediments approximately 14,000-20,000 years old, to the mosaic of more rugged or elevated areas related to

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[17] ISA, Draft Regulations on Exploitation of Mineral Resources in the Area - The President's Further Revised Draft Text, ISBA/28/C/WOW/CRP.2, 5 October 2023, Draft Regulation 20.

[18] These figures are based on old technology. Modern equipment may raise less sediment.

geologically defined horst and graben structures, as well as seamounts remaining after mining (Volkmann and Lehnen, 2017; Kuhn et al., 2020).

Nodule mining will cause loss of essential habitats, including the structural habitat required by some faunal groups (Amon et al., 2016; Vanreusel et al., 2016; Leitner et al., 2017; Stratmann et al., 2021). This type of strip-mining will also substantially and persistently impact food web integrity, i.e. through loss of nodules as a structural habitat for ecological keystone taxa, such as stalked sponges (Stratmann et al., 2021).

The clearing of nodules also incurs the loss of a distinct sediment microhabitat (Wu et al., 2013), accompanied by loss of reactive labile total organic carbon (TOC) and bioturbation (Volz et al., 2020), resulting in reduced microbial activity (Vonnahme et al., 2020) and reduced carbon cycling (Sweetman et al., 2018). The most sensitive indicators of sediment disturbance in the deeply oxidised CCZ are (Vonnahme et al., 2020) (i) bioturbation channel connection, (ii) oxygen concentration profiles, (ii) sediment density measurements (via x-ray), (iv) total inorganic carbon, (v) nitrite concentrations, (vi) oxygen utilization/carbon fixation, and (vii) total organic carbon. In the shallow-oxidised Peru Basin, profiles of manganese-oxide concentration in the solid phase are recommended as an indicator of sediment disturbance in addition to the oxygen penetration depth (Paul et al., 2018).

In particular, the following impacts can be expected to affect the sediment and its ecosystems:

First, the nodule collection will disturb the semi-liquid sediment-surface interface and will create a near-bottom plume with substantial amounts of sediment being displaced (Becker et al., 2001). The released sediments will originate from (a) any gear placed on or moved along the seafloor; (b) the separation of nodules from adhering sediments in the collector (Oebius et al., 2001), causing loss of fauna, and (c) nodule crushing either within the collector or in a separate crusher - any leakage will lead to metal slurry polluting the waters (Kim et al., 2021).

Second, equipment that digs into the sediment can have an impact through the direct crushing of buried infauna (animals living in the sediment), by compacting the substrate through increased weight of machinery or equipment (International Seabed Authority, 2010), or conversely, by stirring up the sediment, dislodging animals, and later leaving a suspended sediment cloud that resettles on the seafloor. Effects on the seafloor are likely to be site-specific and depend strongly on the degree of nodule coverage, the type of technology used, the nature of the fauna, the seafloor material (i.e., the sediment), and oceanographic conditions in the area.

Third, intermittent storage dumps of collected nodules or waste material may increase the seafloor area used by the operation [see e.g. Coffey Natural Systems (2008)].

Fourth, the re-sedimentation of the sediment plumes created by operations on the seafloor can cause blanketing and smothering of substantial areas in the vicinity, the size of area depending on discharge and plume characteristics, bottom current strength and seabed morphology (Peukert et al., 2018; Baeye et al., 2021; Purkiani et al., 2021; Haalboom et al., 2022). Aleynik et al. (2017) assume that in the case of nodule exploitation, such plumes will quickly lead to high levels of suspended sediments and accumulations of > 1 cm thick deposited particulates > 5 km away from the mining activity within 10 days, and 1 mm thick deposits > 50 km away after 1 year, which would equate to >1000 times the background sedimentation rates. However, by taking into consideration gravity currents (Muñoz-Royo et al., 2022) and aggregation (Gillard et al., 2019b), the spatial extent of the blanketing plume may be reduced significantly.

Fifth, if hydraulic pumps are to be used, large volumes of water are required to collect and to pump the extracted nodules to a surface vessel. Most of the animals living near the nodules are not able to avoid the suction flow and will be entrained and die subsequently.

The severity of the ecological effects of mining has to be determined as a function of (estimated) recovery time. As the mined nodules and the associated fauna will only regrow over millions of years, the loss of nodules, but also the loss of biotic structure and organic contents is expected to cause permanent benthic community shifts at mined sites (Haffert et al., 2020; Gollner et al., 2021). The processes will lead to lasting effects on the food web (Orcutt et al., 2018; Stratmann et al., 2021), biogeochemical cycle and carbon-fixation (de Jonge et al., 2020; Hollingsworth et al., 2021). The severity of the effects on ecosystem functioning depends on the amount of labile organic matter removed, *i.e.* the lower the resulting bacterial activity becomes, the more severe the disturbance will be (Haffert et al., 2020; Volz et al., 2020; Vonnahme et al., 2020). A reduction of organic matter supply to the deep sea due to an expansion of the oxygen minimum zone and related changes in midwater consumer activity may amplify these effects (Wishner et al., 2018).

4.2 Recommendations for best environmental practices on the seafloor

The following recommendations provided in the literature focus on minimising the degradation of the deep seafloor ecosystem integrity and its functioning during the mining operation.

- Safeguard a sufficient amount of representative seafloor habitats in each contract area based on habitat classification (Vanreusel et al., 2016; Hauquier et al., 2019; Uhlenkott et al., 2020; Uhlenkott et al., 2022).
- Minimise the spatial extent of the mined area. Limit the directly mined area within a region to a level that does not threaten ecosystem integrity (MIDAS Consortium, 2016).
- Mine a deposit as completely as possible, including lower-grade areas. This 'whole-of-a-deposit approach' has been recommended to minimise the areal consumption and ecological damage of mining (Volkmann, 2014, see also ISA Technical Study No. 11). The assumption is that only mining areas with high-grade deposits may compromise DSM for future generations. As such, the literature recommends lowering the cut-off grade mined to include lower-grade deposits. This approach requires a strong

involvement of the Authority in mine planning and includes a comprehensive resource and reserve assessment of the proposed mining area and the adoption of a sequential mining plan in order to maximize resource utilization (International Seabed Authority, 2013; Volkmann, 2014).

- Arrange the mining tracks so that undisturbed, pristine areas remain to preserve the natural fauna and provide for 'stepping stones' for dispersal (Thiel et al., 2005; Sharma, 2017; Haeckel et al., 2020). Spatial planning should be employed to arrange mined and preserved areas, considering the needs of fauna, the likely dispersal of plumes (Haeckel et al., 2020) and the need not to impact areas outside the contract area. Spatial planning should also avoid conflicts with other human uses of the seafloor, e.g. cable laying (International Seabed Authority, 2015).
- Minimise sediment transport to the surface, i.e. clean the nodules at depth and maximise nodule concentration in the riser pipes (Thiel and Forschungsverbund Tiefsee-Umweltschutz, 2001; Sharma, 2010).
- Minimise the weight of equipment on the seafloor (Cuvelier et al., 2018) and restrict the penetration of the machinery into the sediment to avoid disturbance of consolidated suboxic - or even anoxic - layers (Thiel and Forschungsverbund Tiefsee-Umweltschutz, 2001; Sharma, 2010), *i.e.* minimise depth of sediment removed/raked to less than 10 cm (Volz et al., 2020; Vonnahme et al., 2020).
- Prevent the mobilisation of heavy metals by not exposing the hypoxic bottom layers, such as in the Peru Basin where the oxygenated zone is limited to a few cm (Koschinsky et al., 2003a; Koschinsky et al., 2003b). Hypoxic situations can be caused also through the discharge of mine tailings or chemical waste (Koschinsky et al., 2003a). The creation of hypoxic situations would increase the concentrations of bio-available metals and might change their speciation, which results in different bioavailabilities and toxicities, eventually leading to levels that would be toxic to animals (Thiel and Forschungsverbund Tiefsee-Umweltschutz, 2001; Koschinsky et al., 2003a).
- Avoid storage piling of nodules which may lead to metal-leaching under reducing conditions (Cuvelier et al., 2018).
- Reduce seawater intake, e.g. by using mechanical collection devices (Weaver and Billett, 2019) instead of hydraulic suction.
- Prevent seafloor blanketing of more than 1 mm thickness (Gillard et al., 2019a) equating to 1000 years of natural sedimentation.
- Plan for recovery. This involves: a) the sequence of mining tracks and succession of mining blocks should consider the predominant current direction to induce re-sedimentation where the seafloor is already disturbed, and thereby avoid disturbance of source populations for recolonisation (Thiel and Forschungsverbund Tiefsee-Umweltschutz, 2001) and b) the size, spacing, location of mine sites should be known, and subject to spatial and temporal planning by ISA in order to ensure sufficient undisturbed source areas for recolonisation are available (Thiel et al., 2005; Haeckel et al., 2020).

5 Benthic boundary layer

In addition to the direct effects of nodule removal from the seafloor, the operation of the mining equipment will have 3-dimensional impacts on the seafloor and water column through plumes, vibrations, noise and lighting (Weaver and Billett, 2019). In particular, the effects of increased turbidity from mining plumes may be the most substantial in the benthic boundary layer (BBL), usually the water layer immediately above the seafloor up to a density stratification at approximately 50 m above the seafloor, which is probably the least known deep sea ecosystem (Christiansen et al., 2020). The BBL hosts specialised benthopelagic organisms such as scavenging amphipods, benthopelagic fish and plankton (Christiansen et al., 2010; Vecchione, 2016; Leitner et al., 2017), is an important region for the dispersal of larvae from benthic organisms (Kersten et al., 2017; Kersten et al., 2019; Patel et al., 2020), and is home to a large number of gelatinous organisms (Childress et al., 1989). Bentho-pelagic coupling is crucial to ecosystem functions from nutrient cycling to energy transfer in food webs and thus particularly sensitive to anthropogenic stressors (Griffiths et al., 2017; Christiansen et al., 2020).

5.1 Operational effects of mining in the benthic boundary layer

Given the near-unknown structure and functioning of the BBL, the multiple stressors from mining will put a particularly high management risk on maintaining ecosystem structure and functioning in the BBL. These risks arise from the following operational effects:

Ambient seawater intake for water jets, suction devices, nodule cleaning and crushing as well as for slurry transport to the surface: Estimates of water removal per single mining operation/collector are > 50,000 m^3 per day (Oebius et al., 2001)[19] sourced from the near-bottom water layers and therefore likely to have substantial intake of benthopelagic organisms, including meroplankton larvae and other less mobile species (Christiansen et al., 2020).

Increased turbidity due to unaltered seafloor sediments raised by mining gear: due to the half-fluid nature and extremely small sediment particle sizes, even the slightest touching of the seafloor will raise plumes consisting of the unaltered sediments stirred up from the upper seafloor. In addition, the turbulence behind the vehicle also stirs up sediments. These particles will settle over time

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[19] NOAA (1981) calculated 100,000 m^3 per day including bottom water and interstitial water for a production of 5500 t DW of nodules, including 783 kg of biota of which 80 % are discharged near the bottom. Weaver et al., 2022. Assessing plume impacts caused by polymetallic nodule mining vehicles. Marine Policy 139, 105011. assumed 30,000 m^3 per day.

depending on particle size and degree of aggregation, but over a different area and accumulating differently from the original state. This may overwhelm plankton and seabed organisms in the process, in particular particle filter feeders, and produce chronic impairment (Weaver and Billett, 2019).

Increased turbidity caused by operational exhaust sediment plumes: The extent of plume dispersal depends on the height and momentum of sediment release, seabed morphology, and water column stratification and mixing (Purkiani et al., 2021). Currently no thresholds exist for the environmental significance of turbidity, and impacts on the pelagic fauna are unknown. However, enhanced loads of inorganic and degraded organic particles may impair respiration, decrease food availability, cause higher energy expenditure, and suppress communication and feeding interactions based on bioluminescence and chemical cues. The most prominent effects are the following:

- Clogging of gills and filtration apparatuses of surface-deposit feeding and suspension-feeding organisms, and the raising of energy expenditure and respiratory cost due to unpalatable, mostly inorganic particles of low nutritional value. Organisms with mucus nets (Robison et al., 2005; Christiansen et al., 2020; Katija et al., 2020) are assumed to be highly sensitive to any additional turbidity (Robison, 2009).
- Impairment of chemosensory, olfactory, bioluminescence and other intra- and interspecies light communication is likely to affect populations and propagation.
- Entombment, or burial by sediment plumes.
- Increased oxygen demand in the lower water column because of organic decay may lead locally to reducing conditions which may enhance the bioavailability of heavy metals from sediments (Ozturgut et al., 1981) as well as an increased nutrient flux from the sediments to the water column.

The scale of horizontal dispersal of the operational sediment plume generated by mining along the seafloor depends on several factors: (a) composition and shape of the sediments (e.g. Muñoz-Royo et al., 2022), (b) the degree of flocculation and formation of a turbidity current (Muñoz-Royo et al., 2022), (c) seabed morphology (Peukert et al., 2018; Gausepohl et al., 2020; Purkiani et al., 2021), (d) background currents (Muñoz-Royo et al., 2022), (e) tidal cycles that will keep bottom currents in motion (Baeye et al., 2021); (f) occasional strong events, such as benthic storms or the propagation of surface storms or eddies to the ocean floor resuspend sediments in at least the benthopelagic mixing zone (Aleynik et al., 2017; Purkiani et al., 2020). The latter may be a regular process which will significantly contribute to the spreading of mining-generated plumes both horizontally and vertically. As the density gradient in the water column between the benthic boundary layer and the bathyal and abyssal waters above is small, sediment clouds require little energy to cross and dissipate up in the water column (Purkiani et al., 2021). A significant vertical spreading of operational plumes was observed also by Haalboom et al., (2022); Muñoz-Royo et al., (2022).

Apart from the horizontal and vertical spatial scale of mining, its effects on connectivity patterns of species and the integrity of communities are critical to determine the lasting effects on ecosystem characteristics. Changes will be based on species-specific sensitivity to increased turbidity and blanketing. Jumars (1981) suggests that sensitivity to re-sedimentation depends on the life style or feeding guild of benthic taxa, being highest in sessile suspension feeders tolerating but a thin veneer, medium in suspension and surface deposit feeding species at the sediment-water interface, and lowest in infauna (but see also Mevenkamp et al. (2019) who found short-term responses of meiofauna to an artificial 2 cm thick layer of crushed nodule particles). However, all three guilds will suffer when the sedimented layer grows in thickness due to the reduced organic content and therefore food value (Kim et al., 2014) of the resedimented matter. Differential sensitivities to mining-related and climate change pressures will result in altered or novel species interactions (Levin et al., 2020, and literature quoted therein).

A characteristic of deep-sea sampling is that most of the taxa recovered are either unknown or they occur as singletons in the samples or are otherwise rare (which could also be a sampling artefact) (Amon et al., 2022). Rare species are important contributors to ecosystem functioning (Mouillot et al., 2013). Hauquier et al. (2019) assume that it might be mostly the rare genera and species that will be vulnerable to mining-induced changes in their habitat, based on an investigation of the most abundant meiobenthos component, the nematode communities. Unless the fauna and its life history are better known, mining might thus lead to unforeseen and unnoticed losses of essential functional organisms in the deep sea benthic and pelagic food web.

Even weak chemically reducing conditions in the bottom water will dissolve large amounts of heavy metals from the metal deposit in the upper sediment layers (Koschinsky et al., 2003a).[20] These dissolved metals are likely to be bioavailable, depending on the local chemical properties of each metal and of the water, such as pH, alkalinity, amount of organic material and complexing agents, as well as pressure and temperature, and become toxic at a species-specific level (Ramirez-Llodra et al., 2015). The bioavailability of dissolved metals may have lethal or sublethal effects on the fauna manifesting itself in population changes, reduced productivity, respiratory stress, failing reproduction etc. (Hughes et al., 2015; Hauton et al., 2017; Mestre et al., 2017). However, these descriptors are generally unknown, and unlikely to become measurable any time soon.

5.2 Recommendations for best environmental practices in the benthic boundary layer

• The following recommendations provided in the literature focus on minimising the degradation of the benthic boundary layer

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[20] recent (unpublished) research results indicate that even under fully oxic conditions, the picking up and destruction of the nodules increases the level of bioavailable heavy metals (Haeckel pers. com., JPIO MiningImpact Stakeholder meeting 2023).

ecosystem integrity and its functioning during the mining operation. It is recommended to prevent or minimise operational plume development, its potential for dispersal and redeposition through

- design of shape and arrangement of the mine sites: round or more or less square mining area will have a relatively much smaller plume impact areas compared to elongated and widely spaced mining areas (Volkmann, 2014);
- separation of minerals from sediments (or other debris) as close as possible to the seabed to reduce impacts on the water column (Sharma, 2017);
- use of buffer containers attached to the collector to catch the mixture of sediment, cut-off nodule fragments and the remains of benthic biota, discharged in the collector path (Abramowski, 2018);
- horizontal release of sediments close to the bottom (Peukert et al., 2018);
- inducing a high rate of plume re-sedimentation immediately behind the mining collector (Thiel and Forschungsverbund Tiefsee-Umweltschutz, 2001; Cuvelier et al., 2018; Weaver et al., 2022), e.g. by optimizing particle settling for fast and effective flocculation behind the collector (Peukert et al., 2018). Gillard et al. (2019b) 'suggest that the use of elevated sediment discharge (500 mg L–1) under elevated turbulence results in rapid sediment flocculation' which could be induced by a corresponding mining collector and exhaust pipe design. However, a thorough assessment of operational parameters, expected plume regime, and fraction of discharged sediment is required, as 'the balance of forces in the wake does not vary linearly with operational parameters, and the operational parameters themselves might not vary linearly with scale, which could result in fundamentally different operational regimes' (Muñoz-Royo et al., 2022);
- choice of optimal location and time windows for sediment releases considering bottom currents and topography and the tidal flow patterns (Baeye et al., 2021).

• Prevent the reduction of oxygen concentration in the near-bottom water.

• Carefully investigate the potential fate of discharged pre-processing waste material prior to taking decisions about its disposal at any depth. The better option is a zero waste concept (see below).

6 Water column and surface waters

The water column extends from the sunlit upper 200 m (epipelagial) and the mesopelagial (including the faintest light levels down to ca. 1000 m) to the completely dark regions of bathy-, abysso- and benthopelagic waters. The deep pelagic fauna may comprise the largest reservoir of animal diversity on Earth and has crucial roles in ecosystem functioning while providing essential ecosystem services. The deep pelagic habitats have been a comparatively predictable environment for millions of years, and its physical and biological patterns have led to distinct adaptations of its communities (Robison, 2009, quoting Koslow 2007). Therefore, in bathy-, abysso- and benthopelagic waters, organisms are considered least adapted to environmental changes such as increased turbidity, changes in temperature, food supply as well as light and noise pollution, and small absolute increases may lead to acute effects (van der Grient and Drazen, 2022). Epi- and mesopelagial generate the main organic turn-over and production, feeding the entire foodweb. Surface waters are not only the place where the mining platforms and related vessels operate, but has an ecosystem of its own, the neuston, is the interface to air chemistry and wind forcing, and important for avifauna feeding and all air-breathing animals.

6.1 Operational effects in the water column incl. surface waters

A vessel's presence, its operations and traffic to and from land will not only leave a CO_2 footprint (Heinrich et al., 2019) and likely other effluents, but also cause continuous light and noise disturbances of unknown significance and impact surface and deeper water ecosystems through dumping and discharges.

There are three main hazards to water column organisms from DSM operations: a) The vertical lifting process of the nodule slurry (e.g., 80% water, 20% nodule fragments and likely other sediment) is prone to disaggregate any particle aggregations, abrade nodule fragments through mechanical stress, eventually decrease oxygen saturation through decay and therefore raise the solubility of heavy metals. Breakage of the riser or leakage at pumps and storage facilities may therefore release toxic fluids (Hauton et al., 2017; Kim et al., 2021); b) The discharge of sediment-fluid mixtures from the de-watering and pre-processing onboard the surface platform or vessel will result in a mixture of bottom water, fine sediment < 8µm, organic material, and unrecovered nodule fragments (plus eventual additives) being released back into the ocean (Kim et al., 2021). Whereas larger fragments may quickly sediment to the seafloor, Muñoz-Royo et al. (2021) calculate that the fine sediment fraction of 10 µm diameter and less may remain in the water column for one year, transported in any direction for up to 1000 km. Similar estimates were made for a low concentration deepwater plume of Peru Basin sediment (Rolinski et al., 2001; Baeye et al., 2021), not considering the particle aggregation potential. Depending on the grain size distribution in the discharged waste stream, the material would settle on the bottom within a month (coarse) to 10-15 years (90-95% of the particles, fine particles dominate), and with 2-3% of the sediment mass, corresponding to 25-50% by particle numbers remaining in the water column for 20 years (Baeye et al., 2021); and c) Substantial noise could be generated by the slurry in the vertical transport system, and the necessary pumps. Light may be needed for the remote control of the lifting system.

The discharge plume may intercept with commercially relevant fishes in the epi- and mesopelagic zone, potentially leading to spatial conflict of e.g. tuna fisheries in the CCZ mining in the current exploration areas (van der Grient and Drazen, 2021). The plume may also result in fertilisation, eutrophication and acidification as well as warming of sea waters, increase of organic input and increased aggregation leading to changes in the water column processes (Cuvelier et al., 2018). In addition, the plume may introduce heavy metals and other potentially toxic substances from the pre-processing which may become bioavailable and cause biological reaction from behavioural change to mortality (Hauton et al., 2017).

It has been discussed that chemicals may be added to the discharges, *i.e.* currently unknown chemical additives to separate the mineral phases from the waste material and water, which ISA requests to be assessed for potential harmful effects (International Seabed Authority, 2020b). Should any chemicals be used, e.g. for separating solids from liquids, or to further particle aggregations, utmost attention is needed because of their associated toxicity and bioaccumulative potential (Ramirez-Llodra et al., 2015). Dilution plumes and those formed by the finest particle fraction are persistent, have an unlimited dispersal and are likely to pose the greatest threat to pelagic organisms.

6.2 Recommendations for BEP in the water column incl. surface waters

The water column comprises all waters above the benthic boundary layer, including the surface and epipelagic, mesopelagic, bathypelagic and abyssopelagic waters. Recommended measures and BEP include to

- Prohibit any discharges into epipelagic and mesopelagic waters (Drazen et al., 2020; van der Grient and Drazen, 2021), and if unavoidable, then make permission subject to the Waste Assessment Guidance (WAG) in Annex 2 of the London Protocol (2006);[21]
- Minimise waste (covering all discharges and other waste) towards zero and develop zero-waste concept for the operations of all vessels and platforms in the Area. Schriever and Thiel (2013) review proposals for its secondary use, i.e., waste sediment could be deposited on land. If sediment discharge at sea is necessary, discharged sediments with low toxicity could be compacted into rapidly sinking bricks or lumps, or in biodegradable sediment bags, which will minimise the particle content of the waste water (Cuvelier et al., 2018). The pros and cons of further manipulation techniques need to be discussed.
- Maximise the particle recovery during pre-processing of nodules to decrease particulate volume and metal concentration in effluents (Kim et al., 2021).
- Determine the allowable size range of discharged particles with a focus on reducing the fine fraction (Cuvelier et al., 2018).
- Maximise particulate content of waste water discharged into the water column to promote aggregation and flocculation of particles (without chemical additives), but this increases the risk of leaching heavy metal (Koschinsky et al., 2003a).
- Manage the plume characteristics and spread of fall-out area by optimising the discharge depth and its ambient current velocities, stratification and vertical component (Rzeznik et al., 2019), including also tidal streams (Baeye et al., 2021). Rapid dilution to near-background levels as recommended e.g. by van der Grient and Drazen (2022) to reduce acute and chronic effects on the pelagic communities, but limits flocculation of particles and prevents rapid settling of particles (Muñoz-Royo et al., 2021).
- Manage discharge time and frequency as factors which influence environmental effect (van der Grient and Drazen, 2022);
- Use a 'second discharge pipe supported by on-board pumps should be used to return the bottom water and remains of sediment particulates as well as dissolved nutrients and trace metals to the buffer subsystem after on-board separation of nodule fragments' (Abramowski, 2018).
- Instead of a point-release at a certain depth, Cuvelier et al. (2018) propose for the waste water to be discharged along long horizontal or vertical pipes at different points in the water column to increase dilution and decrease overall flow. This would also minimise disturbance of benthic fauna and minimise plume concentrations for pelagic fauna. However, this will result in a low-level contamination of an even larger area with low-value food particles scavenged by e.g. flux- and mucous feeders, and as such influence the plankton foodweb (Christiansen et al., 2020).
- Temperature management of the fluids is crucial to minimise turbulence (Rzeznik et al., 2019). The cold bottom water will warm up during transport and processing, and if reintroduced in the deep may cause convection and mixing.
- Prevent transboundary effects by using buffer zones (Billett et al., 2019).
- Prohibit additives from processing in the discharged waste water to prevent chemical contamination of the water column (Hong et al., 2019).

Over the years, scientists have discussed several options for the reintroduction of effluents from ship-board processing into the water column:

- Discharge in surface waters: There is general agreement among the scientific community that epipelagic waters are not suitable for discharge because of possible interaction with phytoplankton, zooplankton, and fish larvae in the epipelagic zone (Thiel and Forschungsverbund Tiefsee-Umweltschutz, 2001; International Seabed Authority, 2010).
- Discharge below the oxygen minimum zone (OMZ): A permanent OMZ is found at depths between 400 and 800 m in all oceans, where low oxygen concentrations

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[21] see https://www.imo.org/en/OurWork/Environment/Pages/wag-default.aspx.

and low pH values influence metal binding. The NE Pacific is particularly prone to losing oxygen due to climate change, with the OMZ expanding and deepening (Ross et al., 2020). To avoid dissolution of metals from the particulate phase and their accumulation in the OMZ, discharge is recommended below the thermocline and the OMZ (Thiel and Forschungsverbund Tiefsee-Umweltschutz, 2001; International Seabed Authority, 2010) and only in fully oxygenated waters (Koschinsky et al., 2003a).

- Discharge in midwater (200 to 1000 m) is not recommended (Christiansen et al., 2020; Drazen et al., 2020): The deep mesopelagic and bathypelagic food webs are heavily reliant on low-density, very small organic particles and may be affected through clogging of respiratory and olfactory surfaces, filtering apparatuses and mucous nets (e.g., protists, crustaceans, polychaetes, salps, and appendicularians). Decrease in food value is likely to lead to physiological stress and augmented sinking rates, heavy metal content may be elevated. Light will be absorbed and impact on communication, as will the noise produced by the machinery.
- Discharge close to the seafloor: It has been recommended (Thiel and Forschungsverbund Tiefsee-Umweltschutz, 2001; Schriever and Thiel, 2013) to discharge the tailings at bathyal or even abyssal depths close to the seafloor to limit the potential ocean-wide dispersion of tailings particles. Cuvelier et al. (2018) and Drazen et al. (2020) propose to (re)deposit the sediments over the mined tracks. Such disposal would need to be temperature-equilibrated to the *in situ* temperature to reduce the spatial footprint.

Any of these options will need comprehensive evaluation of environmental risks. While mining wastes are excluded from the London Convention/Protocol on dumping,[22] a mining vessels' operational pollution, anti-fouling systems, ballast waters, and waste disposal is likely subject to established environmental protection rules under the regime of the International Maritime Organisation (International Seabed Authority, 2020a). With respect to dumping, the practices under the London Protocol may be viewed as Best Environmental Practice.

Processing at sea including the dumping of mining waste, incl. sediment, in surface waters was proposed in the 1970s, but is not known to be pursued by any contractor at present. Should this lead to the accumulation of toxic waste on the seafloor from dumping reduced and complexing agents (Koschinsky et al., 2003a), this would require special consideration. Any related assessment of impacts on the water column would require long-term experimental investigations into the composition and individual effects of discharged residues - presumably similar to the assessment frameworks elaborated for the deep sea disposal of land mine tailings (Ramirez-Llodra et al., 2015; Vare et al., 2018), eventually regulated to meet standards and procedures of the London Protocol, Annex 2 (International Seabed Authority, 2020a).[23] A list of investigations required prior to taking management decisions is provided in Vare et al. (2018).

Transshipment losses of re-watered nodule ore. This will affect surface waters to an unknown degree as the transshipment technology remains unknown. However, re-wetting of the nodule ore on the processing ship and pumping of the slurry over to the transport barge appears very likely. This would result in two separate discharge events, as the transported ore will have to be dewatered again.

Accidents have to be accounted for, such as breakage and leakage of hydraulic lines, riser pipe (slurry dumps), oil pollution from surface vessels, or loss of cargo in heavy seas with subsequent surface plumes.

7 Noise, vibrations and light

The natural environment of the deep oceans may be cold, clear, and dark, but certainly not silent as animals communicate over short and large distances and other geophysical events cause noise (Stocker, 2002; Duarte et al., 2021). Marine animals produce sounds between 10 Hz and 20 kHz for intra- and interspecies purposes, including navigation, foraging, agonistic displays, territorial defense, mate attraction, and reproductive courtship (Duarte et al., 2021). For example, some deep sea fish species use low sound frequencies to communicate (Miller et al., 2018, quoting Rountree et al., 2012), and benthopelagic invertebrates are suspected to use sound to detect food falls up to 100 m away (Stocker, 2002). However, Duarte et al. (2021) demonstrate, that today in many parts of the ocean the sound produced by anthropogenic sources overrules the natural soundscape, affecting marine animals at multiple levels, including their behaviour, physiology, and, in extreme cases, survival.

Natural light only occurs in the upper layers, where it is very dim, monochromatic, and downwelling, and affects vertical migration (Aksnes et al., 2017). Deeper down many taxa produce their own light. Bioluminescence and olfaction are, among other senses, important means of communication in the lightless depths. Bioluminescence has now been detected throughout the oceans (Heger et al., 2008) and is important for mate finding, camouflage,

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[22] 1996 London Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matters, 1972, Article 1(4)(3); 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matters, Article 3(2)(c).

[23] see ISA Technical Study No. 25, 2022, p. 42: Waste Assessment Guidelines under the London Convention and Protocol (IMO, 2014). The Guidelines provide for eight distinct steps: (1) waste characterization; (2) waste prevention audit and management options; (3) action list; (4) selection of a dump site; (5) impact assessment; (6) permitting system; (7) permit conditions; and (8) monitoring. These include guidelines for dredged materials, which could be relevant depending on technologies used to exploit resources of the Area. See also Revised Specific Guidelines for the Assessment of Vessels, adopted by LC 38/16 (2016).

prey attraction and fending off predators (Robison, 2004). Sensing sound, scent and electromagnetic fields also appears to be common in deep pelagic organisms, but little is known about their functions, and there is urgent need for more studies (Robison, 2004). Most organisms inhabiting this environment possess highly sensitive visual systems, for example, predatory mid-water fish and squid frequently have highly developed eyes, to be functional in even the dimmest illumination (Robison, 2009), which makes them vulnerable to e.g. bright artificial lights of deep sea operations.

7.1 Effects of noise, vibrations and light

Mining operations on the international seabed will require the continuous presence of a fleet of vessels powering the mining operations as well as traffic to and from land. This generates large amounts of carbondioxide exhaust (Heinrich et al., 2019) and continuous light and noise (McKenna et al., 2012) disturbance of unknown significance in this relatively quiet part of the ocean, which has been described as one of the last wildernesses on Earth (Jones et al., 2018b; Duarte et al., 2021). All industrial activities produce some **noise**, possibly covering the full frequency bandwidth of animal sounds and traveling long distances under water. Mineral extraction produces some of the loudest noises (Stocker, 2002), and Williams et al. (2022) estimate that a single mine may change the sound environment and elevate noise levels audible up to at least 500 km from the source under favourable weather conditions. Also Duarte et al. (2021) consider the dispersal range of operational noise for subsea mining to reach 100 km. Depending on the frequency and depth, e.g. in the so-called SOFAR channel sound can propagate much longer distances (Duarte et al., 2021), interfering with communication of marine mammals. Furthermore, manmade noise may mask inter- and intraspecies communication (Erbe et al., 2016). The great dispersal range may render a meaningful comparison of Impact Reference Zones, IRZ, with Preservation Reference Zones, PRZ,[24] impossible and should thus be a major concern for regulators and mining operators (Williams et al., 2022).

As a first step, Martin et al. (2021) reviewed available knowledge on the likely noise generation of polymetallic nodule mining operations and its documented effects on the marine fauna. They also draw on similar activities in other industries to estimate potential impacts. However, knowledge is scarce, even to predict the actual masking effects of anthropogenic sound on e.g. marine mammals (Erbe et al., 2016). Yet, generally, there is evidence that anthropogenic noise not only impacts marine mammals, but negatively affects both pelagic and benthic fish and invertebrate communities through changes in organisms' behaviour, anatomy, development and physiology (Duarte et al., 2021).

Artificial light in the deep sea may have various effects due to the natural clarity of the water on the one hand, and the high sensitivity of pelagic organisms to light on the other (Douglas et al., 1995; Haddock et al., 2010). Some fishes are known to be attracted to light, whereas others avoid light or do not show any reactions (Widder et al., 2005; Raymond and Widder, 2007; Ryer et al., 2009). Attraction to light may enhance the danger of, for example, entrainment. The ecological function of bioluminescence, e.g. to attract social partners or prey, is likely to be locally masked by bright illumination. A well-lit mine may function as a population sink over a very large area for deep-sea organisms attracted to light. Furthermore, the extremely high intensity of flood lights, as compared to bioluminescence, may irreversibly damage the eyes of organisms in the vicinity, as suggested for vent shrimps by (Herring et al., 1999). A literature review[25] confirms that physiological damage to the eyes of a range of taxa may be caused, depending on exposure and light characteristics. However, so far little is known about the quality and quantity of light needed for the mining operations.

Very little is known about the effects of vibrations caused by activities contracting the seabed on marine life, and nothing in relation to deep seabed mining. However, it can be assumed that at least benthic invertebrates can detect and react to vibrations including those from anthropogenic sources (Roberts and Elliott, 2017).

Environmental risk is determined by the severity of the effects and the intensity, duration and probability of noise, light or vibration occurring, however, to date few estimates have been published on emissions of mineral extraction (Kaikkonen et al., 2018; Martin et al., 2021), due also to technological developments being contractor-specific and rapidly emerging. Future mining tests and targeted studies will hopefully reveal some of the characteristics which should be instrumental to developing BEP.

7.2 Recommendations for BEP to minimise light and noise pollution

A BEP Standard for noise, light and vibration emissions during DSM activities needs to be developed. Based on a comprehensive risk assessment, this will require strict mitigation at the source for all elements of the mining chain, including surface operations. A best available technology standard should implement minimum requirements. As a basic requirement, a "rule explicitly stipulating that introduction of energy, including underwater noise, in mined areas and their vicinity should be at levels that do not adversely affect marine life and the marine environment" should be adopted (Martin et al., 2021).

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[24] PRZ are reference sites which shall inform on the level of disturbance caused by mining in representative mine areas, IRZ. Both zones are to be designated within the contract areas. For details see International Seabed Authority, 2018. Design of IRZs and PRZs in deep-sea mining contract areas. Briefing paper 02/2018. Kingston, Jamaica, pp. 1-8.

[25] Kochevar, R.E., 1998. Effects of Artificial Light on Deep Sea Organisms: Recommendations for ongoing use of artificial lights on deep sea submersibles. https://montereybay.noaa.gov/research/techreports/trkochevar1998.html.

A BEP noise regime needs to consider all sources of noise inherent with the operations, including during exploration and test mining. The spatial and temporal footprint of the noise planned to be emitted needs to be determined, including its short- to long-term lethal and sublethal effects on the habitat and communities affected (Kaikkonen et al., 2018; Martin et al., 2021; Williams et al., 2022). It is strongly recommended to avoid the introduction of noise at depths of the SOFAR channel (typically at depths of 700 to 1,300 meters) to avoid the spreading of noise over thousands of kilometers (Drazen et al., 2020). This would also have to apply for any riser pipe or pumps at that depth. A temporal scheme of periods of active mining alternating with pauses to facilitate survival, animal condition, animal migration, reproductive success and recruitment of benthic and pelagic communities should be considered (Cuvelier et al., 2018).

Existing technical standards and design requirements may be of some help, as recommended for example by Hitchin et al. (2022) and Martin et al. (2021). However, there may only be limited transferability of knowledge gained from coastal to offshore waters (Kaikkonen et al., 2018). For vessels operating outside areas of national jurisdiction, the IMO voluntary guidelines for reducing underwater noise from commercial ships,[26] could be instrumental to develop vessel standards. Best practice may require that ships and underwater operations are to be powered by electric energy which would also minimise noise and vibration emissions (Cuvelier et al., 2018; Duarte et al., 2021).

A BEP light regime should also consider a) the minimum need for light e.g. for the operations, b) its maximum duration and c) maximum intensity as well as a least invasive spectrum (rapidly absorbed light temperature, e.g. around 2000 K), and d) options to minimise light use. Furthermore, the effects of the indispensable light for the operations have to be investigated further to make informed decisions rather than guesses on physiological, behavioural or population changes in affected species or populations. A BEP light regime for surface operations should minimise the disturbance of seabirds and the attraction of other organisms such as cephalopods and marine turtles. This may include the use of red light (Widder et al., 2005).

Ideally, the emission of noise should be restricted to higher frequencies with a fast attenuation, and the use of light should be completely avoided in the deep sea.

8 Overarching recommendations

Overall, a highly precautionary, ecosystem approach to regulating mining operations is essential, focusing on the collection of additional knowledge while avoiding harm as much as possible (Martin et al., 2021; Williams et al., 2022). The authors recommend an iterative approach to noise regulation starting with highly cautious thresholds enabling rapid management responses and full transparency. Acceptable exposure to sediment plumes should also start with concentrations close to background levels (van der Grient and Drazen, 2022). The thresholds relate to the risks posed to fauna by all mining-related stressors individually and combined (Wedding et al., 2022). This requires strategic environmental goal setting by the ISA, an adaptive governance and a strong scientific programme to reduce scientific and management uncertainties (Jaeckel, 2016; Jaeckel, 2017; Jaeckel, 2020). Existing standards and practices from other offshore industries, e.g. for noise pollution, while indicative, need to be thoroughly tested in the deep sea and offshore context, but may only be applicable to a limited extent (Hitchin et al., 2022).

Before any relevant environmental standards for nodule mining in the Area can be developed, scientifically meaningful and robust environmental baselines have to be established for each contract area and the corresponding region (Billett et al., 2019; Amon et al., 2022; Christiansen et al., 2022a), including the mapping of background noise levels (Martin et al., 2021). Therefore, baseline investigations need to inform the location of the mining area and its corresponding representative reference areas, used to determine mining impacts from the very start of operations in their full ecological context (Jones et al., 2018a; Hao et al., 2020; International Seabed Authority, 2020c). Baselines should also determine habitats, species and ecosystem functions to be preserved. The criteria developed by FAO (2009) and Secretariat of the Convention on Biological Diversity (2009) can guide the positioning of additional no-mining areas of the region(s) and contract areas, in order to preserve essential habitats and communities (Christiansen et al., 2022b). For all BEP standards, it is of utmost importance to observe the pelagic and benthic heterogeneity of the regions in question, e.g. the CCZ, which do not constitute one homogenous region and thus cannot be managed as such (Leitner et al., 2017; Drazen et al., 2021; Leitner et al., 2021; Simon-Lledó et al., 2023).

Temporal or spatial avoidance of certain areas by DSM-related activities as well as the avoidance of especially harmful gear was pointed out as an important precautionary mechanism to deal with uncertainty and as a tool for passive adaptive management (Billett et al., 2019). For example, Cuvelier et al. (2018); Haeckel et al. (2020); Hauquier et al. (2019) and Vanreusel et al. (2016) strongly advocate for the incorporation of additional no-mining sites within each of the contract areas (supplementing the PRZ) for the sole purpose of buffering the inevitable loss of biodiversity. Outside contract areas, the network of ‘Areas of Particular Environmental Interest, APEI, in the CCZ has recently been updated to better cover the spectrum of regional and local habitats across the CCZ,[27] including the core oxygen minimum zone currently not covered by the APEIs (Perelman et al., 2021).

Wagner et al. (2020) suggest that in line with a precautionary approach to ensuring effective protection, mining activities should not be allowed to proceed as long as it cannot be demonstrated that vulnerable marine ecosystems (VME, FAO, 2009) will not be subjected to lasting harm. For example, VMEs such as corals and sponges occur on hard substrate including nodules, rugged terrain, and seamounts within the contract areas. Such habitats will not be directly mined, however may suffer from activities and sediment blanketing. Therefore, a VME definition adapted to the risks of deep seabed mining is required (Christiansen et al., 2019).

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[26] www.imo.org/en/MediaCentre/HotTopics/Pages/Nois.aspx.

In addition, Cuvelier et al. (2018) propose to identify seasons or periods during which mining should be restricted or avoided. These "resting periods" (no noise, light and sediment plumes) might help to maintain life functions for the pelagic fauna during critical periods.

Tilot (2019) points to the high importance of preserving the very distinct oldest water masses located in the North-East Pacific between 1800 and 3500 m depth (quoting Talley et al., 2011), which have unique properties due to their perpetual circulation in the deep ocean. The unique biogeochemistry and microbial flora in these waters are presumed to have an impact on the nodule ecosystem (Tilot, 2019). Mining might pollute these waters, for example, through accidents or unregulated leakages from the riser pipes, as well as through wastewater discharge plumes.

Billett et al. (2019) suggest that the full environmental costs should be considered when designing mining equipment, to minimise harm from the start. Additionally, Billett et al. (2019) advocate for the equipment design process to consider mitigation measures at the earliest possible point in time, alongside best available technologies and practices, and cooperation among contractors to advance industry standards and protocols.

Once mining starts, mechanisms should be in place to meticulously observe the intensity and scale of the disturbances, in order to be able to adapt the respective environmental standards and activities to prevent risks and harm to the marine environment (Cormier and Lonsdale, 2020).

9 Towards a standard for BEP

We recommend the ISA to use the scientific recommendations compiled above for starting the development of a first Best Environmental Practice Standard for polymetallic nodule mining operations in the Area. At present, most knowledge and recommendations exist for the Clarion-Clipperton Zone and the Peru Basin. Substantial scientific investigations will be needed for other regions. An ISA Standard for BEP should include operational best practice, maximum permissible emissions, and the environmental framework conditions to be maintained. It would thus build on the environmental goals and objectives to be formulated by the ISA globally and regionally, and the corresponding environmental thresholds, a first set of which are currently being developed.[28] A first BEP standard should be available prior to the first applications for exploitation being received, to allow the ISA to assess an applicant's ability to meet BEP. The BEP Standard should be periodically reviewed, based on results from DSM monitoring programmes and scientific progress.

Building on the scientific recommendations on BEP for polymetallic nodule mining cited above, we compile in Box 1 a preliminary list of elements for a management framework that can underlie a future BEP standard (the "what"). This list is probably not exhaustive, but we hope it provides a starting point for developing a detailed and scientifically sound understanding of the BEP for polymetallic nodule mining in the Area.

10 Final considerations

Using best environmental practice for mineral exploration and exploitation in the Area is a legal obligation for the ISA, contractors, and sponsoring states. Whereas environmental standards such as BEP, BAT and GIP,[30] are frequently referred to in the ISA draft exploitation regulations (as of 2023)[31], there is still no agreed understanding of what constitutes current BEP in relation to deep seabed mining, nor are there any agreed processes at ISA to arrive at some (preliminary) conclusions in parallel with the development of the exploitation regulations. This may prevent that the ISA can apply uniform standards to all applications for exploitation contracts. In addition, the development of BEP in the Area and its regions is tightly linked to the as yet undefined global and regional environmental goals and objectives within the ISA to guide the development of a system of precautions in order to avoid unintended, uncontrolled and unnoticed environmental degradation.

Science has a key role to play in informing the development of BEP prior to the commencement of commercial mining. Biological responses to small-scale experimental disturbance events over several decades (Gollner et al., 2017; Jones et al., 2017) provide invaluable indications of what limits need to be set for mining-related interferences in the deep sea. Scientific monitoring and assessment of test mining[32] (Boetius and Haeckel, 2018; Haeckel et al., 2020; Amon et al., 2022) brings this knowledge to a new scale with more informed recommendations for a first set of BEPs. To close current gaps in knowledge, Amon et al. (2022) propose a road map for scientific exploration, including better access to contractor environmental data. However, BEP development will also require effective stakeholder participation, e.g. for fisheries (van der Grient and Drazen, 2021) and the cable industry (International Seabed Authority, 2015) as well as harmonization with existing maritime regulation (International Seabed Authority, 2020a).

If mining commences, the monitoring of operations and related environmental effects on various scales are crucial to verify compliance

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[27] see ISBA/26/C/58. Decision of the Council of the International Seabed Authority relating to the review of the environmental management plan for the Clarion-Clipperton Zone. December 2021. https://www.isa.org.jm/documents/isba-26-c-58/.

[28] ISA, Decision of the Council of the International Seabed Authority Relating to the Development of Binding Environmental Threshold Values, ISBA/27/C/42, 11 November 2022.

[30] Indeed, GIP is referred to most frequently, although such standard may only exist once the industry is mature.

[31] ISA, Draft regulations on exploitation of mineral resources in the Area: Parts IV and VI and related Annexes, ISBA/28/C/IWG/ENV/CRP.1, 2 March 2023.

[32] A great number of references in the earlier sections derive from the JPIO MiningImpact project (https://miningimpact.geomar.de/publications;jsessionid=474EFC7BEDC6D8537B80D22A89BE0758) and some other such scientific studies.

BOX 1 Recommendations on elements for a future BEP Standard for polymetallic nodule mining operations.

Management framework

1. The overall lack of knowledge on the effects of mining operations on the marine ecosystem requires a highly precautionary, gradual approach, which includes the collection of more knowledge while avoiding harm as much as possible.
2. Comprehensive environmental baseline information of a contract area and its region are essential to developing best operational practice;
3. The spatial and temporal footprint of mining related pressures and needs to be determined, including its short- to long-term lethal and sublethal effects on affected communities.
4. Ecosystem-based, comprehensive risk assessment of the hazards from mining operations is needed for determining BEP to maintain benthic and pelagic processes, taking account of cumulative and synergistic effects, including of climate change.
5. A spatial planning process is recommended to optimise the location and design of the mine sites, the before-after control areas IRZ and PRZ, and other sites in need of protection.
6. Non-mining areas (APEIs, MPAs, VMEs[29] and other types) should be established and effectively conserved within and outside the contract areas to safeguard the Area's ecological values in line with the Azores Criteria (Secretariat of the Convention on Biological Diversity, 2009) and others;
7. Seasons or periods during which mining should best be restricted or avoided need to be considered;
8. Consideration of all environmental costs should lead to mitigation measures embedded into equipment design and result in minimising harm; and
9. Adaptive governance is needed to regulate activities in line with environmental goals and thresholds based on high-intensity monitoring of the disturbances and the effects caused.

Operations affecting the seafloor (based on section 4.2)

A best practice standard should determine technical design and operational practice requirements which facilitate to

1. Minimise and control sediment disturbance and removal, including biogeochemical sediment parameters, bioturbation, and oxygen profile of the sediments; and
2. Minimise the extent of the mine site by determining a sustainable cut-off grade for nodule mining, and by implementing a Whole-of-a-deposit policy;
3. Minimise the contact of the equipment with the seafloor;
4. Minimise water intake;
5. Prevent the release or mobilization of heavy metals;
6. Avoid storage dumps.

Operations affecting the Benthic Boundary Layer (based on section 5.2)

A best practice standard should determine technical design and operational practice requirements which

1. Operationalises a zero waste concept including to prevent operational plume discharge and dispersal. Alternatively, minimise operational plume generation;
2. Determines a maximum impact area for sediment plumes, and gives criteria for determining the affected area and the relevant environmental effects
3. Sets operational limits for
    a) the discharge of sediments at the source (concentration, height above seafloor and volume of release, max. concentrations of metals);
    b) the maximum blanketing thickness in a mined area;
    c) allowable re-sedimentation patterns (spatial extent, thickness within and beyond mine site, temporal development, maximum range of particle dispersal, and protection of areas outside contract area);
    d) the maintenance of oxygen concentration in water and sediment;
    e) the prevention of heavy metal concentrations in plume and sediment fall-out.

Operations affecting the water column and surface waters (based on section 6.2)

A best practice standard should

1. Provide a BEP framework for ship-based processing/beneficiation waste treatment and transport to shore including requirement to minimize greenhouse gas emissions from the operations;
2. Require fully enclosed riser pipes (with a double hull reducing noise propagation);
3. Develop and operationalise a zero-waste concept, where possible, to prevent/minimise the creation and discharge of waste material into the water column; alternatively,
4. Define minimum discharge water quality standards (e.g., sediment load and composition, time and frequency of discharges, temperature, toxic potential, quantity and quality of additives, if at all permitted) informing the shipboard processing and transshipment of material;
5. Prescribe the documentation needs to prove that no environmental harm will follow from any discharges. Therefore, *á priori* investigations of the quality, quantity and fate of potential waste effluents over appropriate temporal and spatial scales are needed.
6. Recommend technical factors to be considered when discharging waste fluid after shipboard processing (incl. volume, pressure, and maximum dispersal);
7. Require a concept for preventing leakages of hydraulic oil etc. within a contingency plan (as well as all hydraulic oil to be fully biodegradable on all vessels and in all submarine machinery);

Operations as a source of noise, vibrations and light (based on section 7.2)

A best practice standard will have to require strict mitigation at the source for all elements of the mining chain, including surface operations. A Best Available Technology standard should implement minimum equipment standards for minimising noise and light pollution from seafloor to surface.

1. Ships and underwater operations are to be powered by electric energy, to minimise greenhouse gas emissions, noise and vibrations.
2. A light regime should be developed for surface operations to minimise the disturbance of seabirds and the attraction of other organisms such as cephalopods and marine turtles.
3. In addition, it is proposed to establish a temporal scheme of periods of active mining alternating with pauses to facilitate survival, animal condition, reproductive success and recruitment of benthic and pelagic communities. Furthermore,
4. It is strongly recommended to avoid the emission of any noise into the SOFAR channel (typically at depths of 700 to 1,300 meters at mid-latitudes) to avoid the spreading of noise over thousands of kilometers.
5. Maximum allowable light and noise emissions should be quantified and qualified in a stepwise process, for all activities involved in the mining operations, eventually building on existing technical standards and design requirements.

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[29] "Areas of Particular Environmental Interest", "Marine Protected Areas", "Vulnerable Marine Ecosystems".

but also to check the appropriateness of the *à priori* determined environmental standards to provide for effective environmental protection. Gerber and Grogan (2020) assume it unlikely that the environmental impacts of mining activities, once commenced, can be fully verified by independent monitoring. They propose a staged monitoring approach with a highly intensive, real-time 'validation monitoring' in the early phases of the project to ascertain that environmental standards are maintained. In this early phase of mining, uncertainties are highest (Smith et al., 2020), which makes it imperative to validate the *à priori* determined contract conditions (Ginzky et al., 2020), including a review of the appropriateness of the first set of BEP. Subject to the monitoring and assessment results of commercial-scale mining, the standards may need to be adjusted to maintain the desired *in situ* conditions. An alternative approach would be to require an *in situ* test of the mining system of significant scale and duration on the basis of which the standards and BEP can be set. Another alternative would be for contractors to only be allowed to commence with a small-scale project where monitoring should demonstrate the effective protection of the environment.

Unlike in traditional industries, Gerber and Grogan (2020) recommend that required standards for e.g. BEP be limited to those "adopted, approved, or issued by the ISA from time to time." This allows for some flexibility in adopting new standards. In this way, standards can be applied uniformly to all contractors, while the ISA and sponsoring states can maintain oversight and due diligence. This requires a corresponding highly precautionary and adaptive ISA governance system (Jaeckel, 2016; Craik, 2020), which in effect establishes a management cycle that requires contractors to adapt their operations to regularly updated environmental performance standards.

Such an ecosystem-based environmental management framework does not exist yet, and the future standards and thresholds remain vague at present. Yet it is high time to have a discussion about what constitutes BEP and how to get there given that some exploration contractors are considering to venture into commercial-scale mineral exploitation. By offering a review of the recommendations made by scientists on possible BEP in all ocean layers, we hope to set a starting point for a science-based process to developing a BEP Standard for polymetallic nodule mining.

With so much scientific uncertainty remaining about the environmental impacts of seabed mining (Amon et al., 2022), States, NGOs, scientists and others have called for a pause on DSM[33] to give effect to the precautionary principle and improve our understanding of deep ocean ecosystems and their vulnerability to the effects of DSM. One might argue that if and when widespread support for postponing DSM exists, such a delay or pause may itself be regarded as BEP.

Author contributions

SC conceived and created the manuscript and researched the literature. All authors contributed to the article and approved the submitted version.

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Conflict of interest

SB was employed by company BioConsult SH. SB was also employed at the ISA Secretariat as Scientific Affairs Officer from 2013 to 2018.

The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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[33] For an overview of current actors that support a moratorium or pause on seabed mining, see https://savethehighseas.org/moratorium_2022/.

References

Abramowski, T. (2018). Environment protection policy and monitoring systems for polymetallic nodules exploitation. *New Trends Production Eng.* 1 (1), 523–529. doi: 10.2478/ntpe-2018-0065

Aksnes, D. L., Røstad, A., Kaartvedt, S., Martinez, U., Duarte, C. M., and Irigoien, X. (2017). Light penetration structures the deep acoustic scattering layers in the global ocean. *Sci. Adv.* 3 (5), e1602468. doi: 10.1126/sciadv.1602468

Aleynik, D., Inall, M. E., Dale, A., and Vink, A. (2017). Impact of remotely generated eddies on plume dispersion at abyssal mining sites in the Pacific. *Sci. Rep.* 7 (1), 16959. doi: 10.1038/s41598-017-16912-2

Amon, D. J., Gollner, S., Morato, T., Smith, C. R., Chen, C., Christiansen, S., et al. (2022). Assessment of scientific gaps related to the effective environmental management of deep-seabed mining. *Mar. Policy* 138, 105006. doi: 10.1016/j.marpol.2022.105006

Amon, D. J., Ziegler, A. F., Dahlgren, T. G., Glover, A. G., Goineau, A., Gooday, A. J., et al. (2016). Insights into the abundance and diversity of abyssal megafauna in a polymetallic-nodule region in the eastern Clarion-Clipperton Zone. *Scientific Reports* 6, 30492. doi: 10.1038/srep30492

Baeye, M., Purkiani, K., de Stigter, H., Gillard, B., Fettweis, M., and Greinert, J. (2021). Tidally driven dispersion of a deep-sea sediment plume originating from seafloor disturbance in the DISCOL area (SE-Pacific Ocean). *Geosciences* 12 (1), 8. doi: 10.3390/geosciences12010008

Becker, H. J., Grupe, B., Oebius, H. U., and Liu, F. (2001). Behavior of deep-sea sediments under the impact of nodule mining processes. *Deep Sea Res. II* 48, 3609–3627. doi: 10.1016/S0967-0645(01)00059-5

Billett, D. S. M., Jones, D. O. B., and Weaver, P. P. E. (2019). "Improving environmental management practices in deep-sea mining," in *Environmental Issues of Deep-Sea Mining. Impacts, Consequences and Policy Perspectives*. Ed. R. Sharma (Cham, Switzerland: Springer Nature Switzerland AG), 403–446.

Boetius, A., and Haeckel, M. (2018). Mind the seafloor. *Science* 359 (6371), 34. doi: 10.1126/science.aap7301

Brown, C. G. (2018). Mining at 2,500 fathoms under the sea: thoughts on an emerging regulatory framework. *Ocean Sci. J.* 53 (2), 287–300. doi: 10.1007/s12601-018-0033-z

Childress, J. J., Gluck, D. L., Carney, R. S., and Gowing, M. M. (1989). Benthopelagic biomass distribution and oxygen consumption in a deep-sea benthic boundary layer dominated by gelatinous organisms. *Limnology Oceanography* 34 (5), 913–930. doi: 10.4319/lo.1989.34.5.0913

Christiansen, B., Denda, A., and Christiansen, S. (2020). Potential effects of deep seabed mining on pelagic and benthopelagic biota. *Mar. Policy* 114. 103442. doi: 10.1016/j.marpol.2019.02.014

Christiansen, B., Bühring, S., Pfannkuche, O., and Weikert, H. (2010). The near-bottom plankton community at the Porcupine Abyssal Plain, NE-Atlantic: Structure and vertical distribution. *Mar. Biol. Res.* 6 (2), 113–124. doi: 10.1080/17451000903150363

Christiansen, S., Bräger, S., and Jaeckel, A. (2022a). Evaluating the quality of environmental baselines for deep seabed mining. *Front. Mar. Sci.* 9. doi: 10.3389/fmars.2022.898711

Christiansen, S., Durussel, C., Guilhon, M., Singh, P., and Unger, S. (2022b). 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. doi: 10.3389/fmars.2022.720146

Christiansen, S., Jaeckel, A., and Houghton, K. (2019). *Ecological safeguards for deep seabed mining* (Dessau: German Federal Environment Agency), Final Report UFOPLAN project No. 3715 25200 0. Available ar: https://www.umweltbundesamt.de/en/publikationen/ecological-safeguards-for-deep-seabed-mining.

Coffey Natural Systems (2008). "Environmental impact statement, solwara 1 project. Nautilus minerals niugini limited, main report," in *Coffey Natural Systems* (Brisbane, Australia), 1–226.

Cormier, R., and Lonsdale, J. (2020). Risk assessment for deep sea mining: an overview of risk. *Mar. Policy* 114, 1–8. doi: 10.1016/j.marpol.2019.02.056

Craik, N. (2020). Implementing adaptive management in deep seabed mining: Legal and institutional challenges. *Mar. Policy* 114, 1–8. doi: 10.1016/j.marpol.2018.09.001

Cuvelier, D., Gollner, S., Jones, D. O. B., Kaiser, S., Arbizu, P. M., Menzel, L., et al. (2018). Potential mitigation and restoration actions in ecosystems impacted by seabed mining. *Front. Mar. Sci.* 5. doi: 10.3389/fmars.2018.00467

Deepak, C. R., Shajahan, M. A., Atmanand, M. A., Annamalai, K., Jeyamani, R., Ravindran, M., et al. (2001). Developmental tests on the underwater mining system using flexible riser concept. *Proc. ISOPE Ocean Min. Symposium*, 94–98.

de Jonge, D. S. W., Stratmann, T., Lins, L., Vanreusel, A., Purser, A., Marcon, Y., et al. (2020). Abyssal food-web model indicates faunal carbon flow recovery and impaired microbial loop 26 years after a sediment disturbance experiment. *Prog. Oceanography* 189, 102446. doi: 10.1016/j.pocean.2020.102446

Douglas, R. H., Partridge, J. C., and Hope, A. J. (1995). Visual and lenticular pigments in the eyes of demersal deep-sea fishes. *J. Comp. Physiol. A* 177, 111–122. doi: 10.1007/BF00243403

Drazen, J. C., Leitner, A. B., Jones, D. O. B., and Simon-Lledó, E. (2021). Regional variation in communities of demersal fishes and scavengers across the CCZ and Pacific Ocean. *Front. Mar. Sci.* 8. doi: 10.3389/fmars.2021.630616

Drazen, J. C., Smith, C. R., Gjerde, K. M., Haddock, S. H. D., Carter, G. S., Choy, C. A., et al. (2020). Opinion: Midwater ecosystems must be considered when evaluating environmental risks of deep-sea mining. *Proc. Natl. Acad. Sci.* 117 (30), 17455–17460. doi: 10.1073/pnas.2011914117

Duarte, C. M., Chapuis, L., Collin, S. P., Costa, D. P., Devassy, R. P., Eguiluz, V. M., et al. (2021). The soundscape of the Anthropocene ocean. *Science* 371, (6529). doi: 10.1126/science.aba4658

Erbe, C., Reichmuth, C., Cunningham, K., Lucke, K., and Dooling, R. (2016). Communication masking in marine mammals: A review and research strategy. *Mar. Pollut. Bull.* 103 (1-2), 15–38. doi: 10.1016/j.marpolbul.2015.12.007

FAO (2009). *International guidelines for the management of deep-sea fisheries in the high seas Food and Agriculture Organization of the United Nations Rome* (Rome: Food and Agriculture Organization of the United Nations). 1–73.

Gausepohl, F., Hennke, A., Schoening, T., Köser, K., and Greinert, J. (2020). Scars in the abyss: reconstructing sequence, location and temporal change of the 78 plough tracks of the 1989 DISCOL deep-sea disturbance experiment in the Peru Basin. *Biogeosciences* 17 (6), 1463–1493. doi: 10.5194/bg-17-1463-2020

Gillard, B., Chatzievangelou, D., Thomsen, L., and Ullrich, M. S. (2019a). Heavy-metal-resistant microorganisms in deep-sea sediments disturbed by mining activity: an application toward the development of experimental *in vitro* systems. *Front. Mar. Sci.* 6. doi: 10.3389/fmars.2019.00462

Gillard, B., Purkiani, K., Chatzievangelou, D., Vink, A., Iversen, M. H., and Thomsen, L. (2019b). Physical and hydrodynamic properties of deep sea mining-generated, abyssal sediment plumes in the Clarion Clipperton Fracture Zone (eastern-central Pacific). *Elementa Sci. Anthropocene* 7 (5), 1–14. doi: 10.1525/elementa.343

Gerber, L.J., and Grogan, R.L. (2020). Challenges of operationalising good industry practice and best environmental practice in deep seabed mining regulation. *Marine Policy* 114. doi: 10.1016/j.marpol.2018.09.002

Ginzky, H., Singh, P.A., and Markus, T. (2020). Strengthening the International Seabed Authority's knowledge-base: Addressing uncertainties to enhance decision-making. *Marine Policy* 114, 103823. doi: 10.1016/j.marpol.2020.103823

Gollner, S., Haeckel, M., Janssen, F., Lefaible, N., Molari, M., Papadopoulou, S., et al. (2021). Restoration experiments in polymetallic nodule areas. *Integrated Environ. Assess. Management* 18 (3), 682–696. doi: 10.1002/ieam.4541

Gollner, S., Kaiser, S., Menzel, L., Jones, D. O. B., Brown, A., Mestre, N. C., et al. (2017). Resilience of benthic deep-sea fauna to mining activities. *Mar. Environ. Res* 129, 76–101. doi: 10.1016/j.marenvres.2017.04.010

Government of India (2020) *Environmental Impact Statement - Environmental conditions and likely impact in the area selected for nodule trials at the Indian PMN site in the Central Indian Ocean Basin*. Available at: https://moes.gov.in/writereaddata/files/India_PMN_EIS_Jan_2020.pdf.

Griffiths, J. R., Kadin, M., Nascimento, F. J. A., Tamelander, T., Törnroos, A., Bonaglia, S., et al. (2017). The importance of benthic-pelagic coupling for marine ecosystem functioning in a changing world. *Global Change Biol.* 23 (6), 2179–2196. doi: 10.1111/gcb.13642

GSR (2018). Environmental Impact Statement. Small-scale testing of nodule collector components on the seafloor of the Clarion-Clipperton Fracture Zone and its environmental impact. *Global Sea Mineral Resour.* Global Sea Mineral Resources NV, Zwijndrecht, Belgium, 1–337.

Haalboom, S., Schoening, T., Urban, P., Gazis, I.-Z., de Stigter, H., Gillard, B., et al. (2022). Monitoring of anthropogenic sediment plumes in the Clarion-Clipperton Zone, NE equatorial Pacific Ocean. *Front. Mar. Sci.* 9. doi: 10.3389/fmars.2022.882155

Haddock, S. H. D., Moline, M. A., and Case, J. F. (2010). Bioluminescence in the sea. *Annu. Rev. Mar. Sci.* 2 (1), 443–493. doi: 10.1146/annurev-marine-120308-081028

Haeckel, M., Vink, A., Janssen, F., and Kasten, S. (2020). "Chapter 16 environmental impacts of deep seabed mining," in *New Knowledge and Changing Circumstances in the Law of the Sea*. Ed. T. Heidar (Brill Nijhoff), 327–340. doi: 10.1163/9789004437753_018

Haffert, L., Haeckel, M., de Stigter, H., and Janssen, F. (2020). Assessing the temporal scale of deep-sea mining impacts on sediment biogeochemistry. *Biogeosciences* 17 (10), 2767–2789. doi: 10.5194/bg-17-2767-2020

Handschuh, R., Grebe, H., Panthel, J., Schule, E., Wenzlawiak, B., Schwarz, W., et al. (2001). "Innovative deep ocean mining concept based on flexible riser and self-propelled mining machines," in *The proceedings of the fourth, (2001) ISOPE ocean mining symposium* (Cupertino, CA: International Society of Offshore and Polar Engineers), 99–107.

Hao, H., Lei, W., Danyun, O., Weiwen, L., Fangfang, K., Cai, L., et al. (2020). A preliminary evaluation of some elements for designation of preservation and impact reference zones in deep sea in the Clarion-Clipperton Zone: A case study of the China ocean mineral resources association contract area. *Ocean Coast. Manage.* 188, 105135. doi: 10.1016/j.ocecoaman.2020.105135

Hauquier, F., Macheriotou, L., Bezerra, T. N., Egho, G., Martínez Arbizu, P., and Vanreusel, A. (2019). Distribution of free-living marine nematodes in the Clarion–Clipperton Zone: implications for future deep-sea mining scenarios. *Biogeosciences* 16 (18), 3475–3489. doi: 10.5194/bg-16-3475-2019

Hauton, C., Brown, A., Thatje, S., Mestre, N. C., Bebianno, M. J., Martins, I., et al. (2017). Identifying toxic impacts of metals potentially released during deep-sea mining—A synthesis of the challenges to quantifying risk. *Front. Mar. Sci.* 4, (368). doi: 10.3389/fmars.2017.00368

Heger, A., Ieno, E. N., King, N. J., Morris, K. J., Bagley, P. M., and Priede, I. G. (2008). Deep-sea pelagic bioluminescence over the Mid-Atlantic Ridge. *Deep Sea Res. II* 55, 126–136. doi: 10.1016/j.dsr2.2007.09.014

Heinrich, L., Koschinsky, A., Markus, T., and Singh, P. (2020). Quantifying the fuel consumption, greenhouse gas emissions and air pollution of a potential commercial manganese nodule mining operation. *Mar. Policy* 114, 103678. doi: 10.1016/j.marpol.2019.103678

Herring, P. J., Gaten, E., and Shelton, P. M. J. (1999). Are vent shrimps blinded by science? *Nature* 398 (6723), 116–116.

Hitchin, B., Smith, S., Kröger, K., Jones, D. O. B., Jaeckel, A., Mestre, N., et al. (2022). Thresholds in deep-seabed mining: A primer for their development. *Mar. Policy* 149, 105505. doi: 10.20944/preprints202207.0270.v1

Hollingsworth, A. L., Jones, D. O. B., and Young, C. R. (2021). Spatial variability of abyssal nitrifying microbes in the north-eastern Clarion-Clipperton Zone. *Front. Mar. Sci.* 8. doi: 10.3389/fmars.2021.663420

Hong, S., Kim, H.-W., Yeu, T., Choi, J.-S., Lee, T. H., and Lee, J.-K. (2019). "Technologies for safe and sustainable mining of deep-seabed minerals," in *Environmental Issues of Deep-Sea Mining. Impacts, Consequences and Policy Perspectives*. Ed. R. Sharma (Cham, Switzerland: Springer Nature Switzerland AG), 95–143.

Hughes, D. J., Shimmield, T. M., Black, K. D., and Howe, J. A. (2015). Ecological impacts of large-scale disposal of mining waste in the deep sea. *Sci. Rep.* 5, 9985. doi: 10.1038/srep09985

ICES (2015). Report of the ICES/NAFO Joint Working Group on Deep-water Ecology (WGDEC), 16–20 February 2015, Horta, Azores, Portugal. ICES CM 2015/ACOM:27. 113 pp.

International Seabed Authority. (2010). *Recommendations for the Guidance of contractors for the Assessment of the Possible Environmental Impacts Arising from Exploration for Polymetallic Nodules in the Area* (Kingston. Jamaica: International Seabed Authority). ISBA/16/LTC/7.

International Seabed Authority. (2013). *Towards the development of a regulatory framework for polymetallic nodule exploitation in the Area* (Kingston, Jamaika: International Seabed Authority), 1–89. Technical Study No. 11.

International Seabed Authority. (2015). *Submarine Cables and Deep Seabed Mining. Advancing Common Interests and Addressing UNCLOS "Due Regard" Obligations* (Kingston, Jamaika: International Seabed Authority), 1–89. Technical Study No. 14.

International Seabed Authority. (2018). "Design of IRZs and PRZs in deep-sea mining contract areas," in *Briefing paper 02/2018*(Kingston, Jamaica: ISA Secretariat), 1–8.

International Seabed Authority. (2020a). "Competencies of the international seabed authority and international maritime organisation in the context of activities in the area. International seabed authority," in *Technical Study No. 25*(Kingston, Jamaika: ISA Secretariat), 1–91.

International Seabed Authority. (2020b). *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/6rev1 (30 March 2020)* (Kingston, Jamaica: Legal and Technical Commission), 40.

International Seabed Authority. (2020c). "Report of ISA workshop on the design of "Impact reference zones" and "Preservation reference zones"," in *Deep-Sea Mining Contract Areas* (Kingston, Jamaica: International Seabed Authority), 41. echnical STudy No. 21.

ITLOS (2011) *Responsibilities and Obligations of States Sponsoring Persons and Entities with Respect to Activities in the Area, Case No. 17, Advisory Opinion (ITLOS Seabed Disputes Chamber Feb. 1, 2011).* Available at: https://www.itlos.org/fileadmin/itlos/documents/cases/case_no_17/adv_op_010211.pdf.

Jaeckel, A. (2016). Deep seabed mining and adaptive management: the procedural challenges for the International Seabed Authority. *Mar. Policy* 70, 205–211. doi: 10.1016/j.marpol.2016.03.008

Jaeckel, A. L. (2017). "The International Seabed Authority and the precautionary principle," in *Balancing deep Seabed Mineral Mining and Marine Environmental Protection* (Leiden, Netherlands: Brill/Nijhoff).

Jaeckel, A. (2020). Strategic environmental planning for deep seabed mining in the Area. *Mar. Policy* 114, 103423. doi: 10.1016/j.marpol.2019.01.012

Jones, D. O. B., Ardron, J. A., Colaço, A., and Durden, J. M. (2018a). Environmental considerations for impact and preservation reference zones for deep-sea polymetallic nodule mining. *Mar. Policy* 118. doi: 10.1016/j.marpol.2018.10.025

Jones, D. O. B., Kaiser, S., Sweetman, A. K., Smith, C. R., Menot, L., Vink, A., et al. (2017). Biological responses to disturbance from simulated deep-sea polymetallic nodule mining. *PloS One* 12 (2), e0171750. doi: 10.1371/journal.pone.0171750

Jones, K. R., Klein, C. J., Halpern, B. S., Venter, O., Grantham, H., Kuempel, C. D., et al. (2018b). The location and protection status of earths diminishing marine wilderness. *Curr. Biol.* 12 (2), e0171750. doi: 10.31230/osf.io/azq53

Jumars, P. A. (1981). Limits in predicting and detecting benthic community responses to manganese nodule mining. *Mar. Min.* 3 (1/2), 213–229.

Kaikkonen, L., Venesjarvi, R., Nygard, H., and Kuikka, S. (2018). Assessing the impacts of seabed mineral extraction in the deep sea and coastal marine environments: Current methods and recommendations for environmental risk assessment. *Mar. pollut. Bull.* 135, 1183–1197. doi: 10.1016/j.marpolbul.2018.08.055

Katija, K., Troni, G., Daniels, J., Lance, K., Sherlock, R. E., Sherman, A. D., et al. (2020). Revealing enigmatic mucus structures in the deep sea using DeepPIV. *Nature* 583 (7814), 78–82. doi: 10.1038/s41586-020-2345-2

Kersten, O., Craig, R. S., and Eric, W. V. (2017). Abyssal near-bottom dispersal stages of benthic invertebrates in the Clarion-Clipperton polymetallic nodule province. *Deep Sea Res. Part I: Oceanographic Res. Papers* 127, 31–40. doi: 10.1016/j.dsr.2017.07.001

Kersten, O., Vetter, E. W., Jungbluth, M. J., Smith, C. R., and Goetze, E. (2019). Larval assemblages over the abyssal plain in the Pacific are highly diverse and spatially patchy. *PeerJ* 7, e7691. doi: 10.7717/peerj.7691

Khripounoff, A., Caprais, J.-C., and Crassous, P. (2006). Geochemical and biological recovery of the disturbed seafloor in polymetallic nodule fields of the Clipperton-Clarion Fracture Zone (CCFZ) at 5000-m depth. *Limnology Oceanography* 51 (5), 2033–2041. doi: 10.4319/lo.2006.51.5.2033

Kim, M. G., Hyeong, K., Yoo, C. M., Lee, J. Y., and Seo, I. (2021). Characterization of fines produced by degradation of polymetallic nodules from the Clarion-Clipperton Zone. *Minerals* 11 (2), 205. doi: 10.3390/min11020205

Kim, H. J., Kim, D., Hyeong, K., Hwang, J., Yoo, C. M., Ham, D. J., et al. (2014). Evaluation of resuspended sediments to sinking particles by benthic disturbance in the Clarion-Clipperton nodule fields. *Mar. Georesources Geotechnology* 33 (2), 160–166. doi: 10.1080/1064119X.2013.815675

Koschinsky, A., Borowski, C., and Halbach, P. (2003a). Reactions of the heavy metal cycle to industrial activities in the deep sea: An ecological assessment. *Int. Rev. Hydrobiology* 88, 102–127. doi: 10.1002/iroh.200390000

Koschinsky, A., Winkler, A., and Fritsche, U. (2003b). Importance of different types of marine particles for the scavenging of heavy metals in the deep-sea bottom water. *Appl. Geochemistry* 18, 693–710. doi: 10.1016/S0883-2927(02)00161-0

Koslow, T. (2007). *The Silent Deep: The Discovery, Ecology, and Conservation of the Deep Sea* (Chicago, Illinois: University of Chicago Press), 270 pp.

Kuhn, T., Rühlemann, C., Wiedicke-Hombach, M., Rutkowski, J., von Wirth, H.-J., Koenig, D., et al. (2011). Tiefseeförderung von Manganknollen. *Schiff Hafen* 5, 78–83.

Kuhn, T., Uhlenkott, K., Vink, A., Rühlemann, C., and Martinez Arbizu, P. (2020). "Chapter 58 - Manganese nodule fields from the Northeast Pacific as benthic habitats," in *Seafloor Geomorphology as Benthic Habitat (Second Edition).* Eds. P. T. Harris and E. Baker (Elsevier), 933–947. doi: 10.1016/B978-0-12-814960-7.00058-0

Kuhn, T., Wegorzewski, A., Rühlemann, C., and Vink, A. (2017). *Composition, Formation, and Occurrence of Polymetallic Nodules*. In: Sharma, R.. (eds) *Deep-Sea Mining.* Springer, Cham. 23–63. doi: 10.1007/978-3-319-52557-0_2

Leal Filho, W., Abubakar, I., Nunes, C., Platje, J., Ozuyar, P., Will, M., et al. (2021). Deep seabed mining: A note on some potentials and risks to the sustainable mineral extraction from the oceans. *J. Mar. Sci. Eng.* 9 (5), 521. doi: 10.3390/jmse9050521

Leitner, A. B., Drazen, J. C., and Smith, C. R. (2021). Testing the seamount refuge hypothesis for predators and scavengers in the western Clarion-Clipperton Zone. *Front. Mar. Sci.* 8. doi: 10.3389/fmars.2021.636305

Leitner, A. B., Neuheimer, A. B., Donlon, E., Smith, C. R., and Drazen, J. C. (2017). Environmental and bathymetric influences on abyssal bait-attending communities of the Clarion Clipperton Zone. *Deep Sea Res. Part I* 125, 65–80. doi: 10.1016/j.dsr.2017.04.017

Levin, L. A., Wei, C. L., Dunn, D. C., Amon, D. J., Ashford, O. S., Cheung, W. W. L., et al. (2020). Climate change considerations are fundamental to management of deep-sea resource extraction. *Global Change Biol.* 26 (9), 4664–4678. doi: 10.1111/gcb.15223

London Protocol (2006). *1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972, as amended in 2006 of 7 November 1996. 36 ILM 1.*

Ma, W., Schott, D., and Lodewijks, G. (2017). Continuous line bucket lifting versus pipe lifting. *J. Offshore Mechanics Arctic Eng.* 139 (5), 051704. doi: 10.1115/1.4036375

Martin, C., Weilgart, L., Amon, D. J., and Müller, J. (2021). "Deep-Sea Mining: A noisy affair," in *Overview and Recommendations* (Wädenswill, Switzerland: Ocean Care), 1–64.

McKenna, M. F., Ross, D., Wiggins, S. M., and Hildebrand, J. A. (2012). Underwater radiated noise from modern commercial ships. *J. Acoustical Soc. America* 131 (1), 92–103. doi: 10.1121/1.3664100

Mestre, N. C., Rocha, T. L., Canals, M., Cardoso, C., Danovaro, R., Dell'Anno, A., et al. (2017). Environmental hazard assessment of a marine mine tailings deposit site and potential implications for deep-sea mining. *Environ. Pollut.* 228, 169–178. doi: 10.1016/j.envpol.2017.05.027

Mevenkamp, L., Guilini, K., Boetius, A., De Grave, J., Laforce, B., Vandenberghe, D., et al. (2019). Responses of an abyssal meiobenthic community to short-term burial with crushed nodule particles in the south-east Pacific. *Biogeosciences* 16 (11), 2329–2341. doi: 10.5194/bg-16-2329-2019

Mewes, K., Mogollón, J. M., Picard, A., Rühlemann, C., Kuhn, T., Nöthen, K., et al. (2014). Impact of depositional and biogeochemical processes on small scale variations in nodule abundance in the Clarion-Clipperton Fracture Zone. *Deep Sea Res. Part I* 91, 125–141. doi: 10.1016/j.dsr.2014.06.001

MIDAS Consortium (2016). *The MIDAS project: research highlights*. 1–44. https://www.eu-midas.net/sites/default/files/downloads/MIDAS_research_highlights_low_res.pdf (accessed 3 November 2023)

Miller, K. A., Thompson, K. F., Johnston, P., and Santillo, D. (2018). An overview of seabed mining including the current state of development, environmental impacts, and knowledge gaps. *Front. Mar. Sci.* 4, (418). doi: 10.3389/fmars.2017.00418

Mouillot, D., Bellwood, D. R., Baraloto, C., Chave, J., Galzin, R., Harmelin-Vivien, M., et al. (2013). Rare species support vulnerable functions in high-diversity ecosystems. *PloS Biol.* 11 (5), e1001569. doi: 10.1371/journal.pbio.1001569

Muñoz-Royo, C., Ouillon, R., Mousadik, S. E., Alford, M. H., and Peacock, T. (2022). An *in situ* study of abyssal turbidity-current sediment plumes generated by a deep seabed polymetallic nodule mining preprototype collector vehicle. *Sci. Adv.* 8 (eabn1219), 1–17. doi: 10.1126/sciadv.abn1219

Muñoz-Royo, C., Peacock, T., Alford, M. H., Smith, J., Le Boyer, A., Kulkarni, C. S., et al. (2021). Assessing the scale of deep-sea nodule mining midwater discharge sediment plumes. *Nat. Commun* 2, 148. doi: 10.1038/s43247-021-00213-8

Niner, H. J., Ardron, J. A., Escobar, E. G., Gianni, M., Jaeckel, A., Jones, D. O. B., et al. (2018). Deep-sea mining with no net loss of biodiversity—An impossible aim. *Front. Mar. Sci.* 5, (53). doi: 10.3389/fmars.2018.00053

NOAA (1981). *Deep seabed mining. Draft programmatic environmental impact statement. U.S. Department of commerce, national oceanic and atmospheric administration* (Washington, D.C., USA: NOAA). 316.

Oebius, H. U., Becker, H. J., Rolinski, S., and Jankowski, J. A. (2001). Parametrization and evaluation of marine environmental impacts produced by deep-sea manganese nodule mining. *Deep Sea Res. Part II: Topical Stud. Oceanography* 48 (17–18), 3453–3467. doi: 10.1016/S0967-0645(01)00052-2

Orcutt, B. N., Bradley, J., Brazelton, W. J., Estes, E. R., Goordial, J. M., Huber, J. A., et al. (2018). Impacts of deep-sea mining on microbial ecosystem services. *Front. Mar. Sci. special issue "Managing Deep Sea Ecosystems"* 65, 1489-1510. doi: 10.1101/463992

Ozturgut, E., Lavelle, J. W., and Burns, R. E. (1981). "Impacts of manganese nodule mining on the environment: Results from pilot scale mining tests in the north equatorial Pacific," in *Marine Environmental Pollution. 2. Dumping and Mining*. Ed. R. A. Geyer Elsevier Oceanography Series, Vol. 27, Part B, 1981, 437–474. doi: 10.1016/S0422-9894(08)71420-X

Patel, T., Robert, H., D'Udekem D'Acoz, C., Martens, K., De Mesel, I., Degraer, S., et al. (2020). Biogeography and community structure of abyssal scavenging Amphipoda (Crustacea) in the Pacific Ocean. *Biogeosciences* 17 (10), 2731–2744. doi: 10.5194/bg-17-2731-2020

Paul, S. A. L., Gaye, B., Haeckel, M., Kasten, S., and Koschinsky, A. (2018). Biogeochemical regeneration of a nodule mining disturbance site: trace metals, DOC and amino acids in deep-sea sediments and pore waters. *Front. Mar. Sci.* 5. doi: 10.3389/fmars.2018.00117

Perelman, J. N., Firing, E., van der Grient, J. M. A., Jones, B. A., and Drazen, J. C. (2021). Mesopelagic scattering layer behaviors across the Clarion-Clipperton Zone: implications for deep-sea mining. *Front. Mar. Sci.* 8. doi: 10.3389/fmars.2021.632764

Peukert, A., Schoening, T., Alevizos, E., Köser, K., Kwasnitschka, T., and Greinert, J. (2018). Understanding Mn-nodule distribution and evaluation of related deep-sea mining impacts using AUV-based hydroacoustic and optical data. *Biogeosciences* 15 (8), 2525–2549. doi: 10.5194/bg-15-2525-2018

Purkiani, K., Gillard, B., Paul, A., Haeckel, M., Haalboom, S., Greinert, J., et al. (2021). Numerical simulation of deep-sea sediment transport induced by a dredge experiment in the northeastern Pacific Ocean. *Front. Mar. Sci.* 8. doi: 10.3389/fmars.2021.719463

Purkiani, K., Paul, A., Vink, A., Walter, M., Schulz, M., and Haeckel, M. (2020). Evidence of eddy-related deep-ocean current variability in the northeast tropical Pacific Ocean induced by remote gap winds. *Biogeosciences* 17 (24), 6527–6544. doi: 10.5194/bg-17-6527-2020

Ramirez-Llodra, E., Trannum, H. C., Evenset, A., Levin, L. A., Andersson, M., Finne, T. E., et al. (2015). Submarine and deep-sea mine tailing placements: A review of current practices, environmental issues, natural analogs and knowledge gaps in Norway and internationally. *Mar. pollut. Bull.* 97 (1–2), 13–35. doi: 10.1016/j.marpolbul.2015.05.062

Raymond, E. H., and Widder, E. A. (2007). Behavioral responses of two deep-sea fish species to red, far-red, and white light. *Mar. Ecol. Prog. Ser.* 350, 291–298. doi: 10.3354/meps07196

Roberts, L., and Elliott, M. (2017). Good or bad vibrations? Impacts of anthropogenic vibration on the marine epibenthos. *Sci. Total Environ.* 595, 255–268. doi: 10.1016/j.scitotenv.2017.03.117

Robison, B. H. (2004). Deep pelagic biology. *J. Exp. Mar. Biol. Ecol.* 300, 253–272. doi: 10.1016/j.jembe.2004.01.012

Robison, B. (2009). Conservation of deep pelagic biodiversity. *Conserv. Biol.* 23 (4), 847–858. doi: 10.1111/j.1523-1739.2009.01219.x

Robison, B. H., Reisenbichler, K. R., and Sherlock, R. E. (2005). Giant larvacean houses: rapid carbon transport to the deep sea floor. *Science* 308 (5728), 1609–1611. doi: 10.1126/science.1109104

Rolinski, S., Segschneider, J., and Sundermann, J. (2001). Long-term propagation of tailings from deep-sea mining under variable conditions by means of numerical simulations. *Deep Sea Res. II* 48, 3469–3485. doi: 10.1016/S0967-0645(01)00053-4

Ross, T., Du Preez, C., and Ianson, D. (2020). Rapid deep ocean deoxygenation and acidification threaten life on Northeast Pacific seamounts. *Global Change Biol.* 26, 1–21. doi: 10.1111/gcb.15307

R. Rountree, F. Juanes, C. Goudey and K. Ekstrom (Eds.) (2012). *Is biological sound production important in the deep sea?* (New York: Springer-Verlag).

Ryer, C. H., Stoner, A. W., Iseri, P. J., and Spencer, M. L. (2009). Effects of simulated underwater vehicle lighting on fish behavior. *Mar. Ecol. Prog. Ser.* 391, 97–106. doi: 10.3354/meps08168

Rzeznik, A. J., Flierl, G. R., and Peacock, T. (2019). Model investigations of discharge plumes generated by deep-sea nodule mining operations. *Ocean Eng.* 172, 684–696. doi: 10.1016/j.oceaneng.2018.12.012

Schriever, G., and Thiel, H. (2013). "Tailings and their disposal in deep-sea mining," in *Proceedings of the Tenth (2013) ISOPE Ocean Mining and Gas Hydrates Symposium*, Szczecin, Poland, September 22-26, 2013. 5–17.

Secretariat of the Convention on Biological Diversity (2009). *Azores scientific criteria and guidance for identifying ecologically or biologically signifi cant marine areas and designing representative networks of marine protected areas in open ocean waters and deep sea habitats* (Montréal, Quebec, Canada: CBD Secretariat), 1–12.

Sharma, R. (2010). First nodule to first mine-site: development of deep-sea mineral resources from the Indian Ocean. *Curr. Sci.* 99 (6), 750–759. https://www.jstor.org/stable/24109602

R. Sharma (Ed.) (2017). *Deep-sea mining: resource potential, technical and environmental considerations* (Cham: Springer). doi: 10.1007/978-3-319-52557-0_17

Sharma, R., Nath, B. N., Parthiban, G., and Jaisankar, S. (2001). Sediment redistribution during simulated benthic disturbance and its implications on deep seabed mining. *Deep Sea Res. II* 48, 3363–3380. doi: 10.1016/S0967-0645(01)00046-7

Simon-Lledó, E., Amon, D. J., Bribiesca-Contreras, G., Cuvelier, D., Durden, J. M., Ramalho, S. P., et al. (2023). Carbonate compensation depth drives abyssal biogeography in the northeast Pacific. *Nat. Ecol. Evol.* 7 (9), 1388–1397. doi: 10.1038/s41559-023-02122-9

Simon-Lledó, E., Pomee, C., Ahokava, A., Drazen, J. C., Leitner, A. B., Flynn, A., et al. (2020). Multi-scale variations in invertebrate and fish megafauna in the mid-eastern Clarion Clipperton Zone. *Prog. Oceanography* 187, 102405. doi: 10.1016/j.pocean.2020.102405

Singh, P., and Christiansen, S. (2022). *Test mining in the legal and environmental governance of the Area – Final Report 3 UFOPLAN project No. 3717252270* (Dessau, Germany: Federal Environment Agency).

Smet, B.d., Pape, E., Riehl, T., Bonifacio, P., Colson, L., and Vanreusel, A. (2017). The community structure of deep-sea macrofauna associated with polymetallic nodules in the eastern part of the Clarion-Clipperton Zone. *Front. Mar. Sci.* 4. Deep-Sea Environments and Ecology. doi: 10.3389/fmars.2017.00103

Smith, C. R., Tunnicliffe, V., Colaço, A., Drazen, J. C., Gollner, S., Levin, L. A., et al. (2020). Deep-sea misconceptions cause underestimation of seabed-mining impacts. *Trends Ecol. Evol.* 35 (10), 853–857. doi: 10.1016/j.tree.2020.07.002

Stocker, M. (2002). Fish, mollusks and other sea animals' use of sound, and the impact of anthropogenic noise in the marine acoustic environment. *J. Acoust. Soc Am.* 112 (5), 2431–2457. doi: 10.1121/1.4779979

Stratmann, T., Lins, L., Purser, A., Marcon, Y., Rodrigues, C. F., Ravara, A., et al. (2018). Abyssal plain faunal carbon flows remain depressed 26 years after a simulated deep-sea mining disturbance. *Biogeosciences* 15 (13), 4131–4145. doi: 10.5194/bg-15-4131-2018

Stratmann, T., Soetaert, K., Kersken, D., and van Oevelen, D. (2021). Polymetallic nodules are essential for food-web integrity of a prospective deep-seabed mining area in Pacific abyssal plains. *Nat. Sci. Rep* 11, 12238. doi: 10.1038/s41598-021-91703-4

Sweetman, A. K., Smith, C. R., Shulse, C. N., Maillot, B., Lindh, M., Church, M. J., et al. (2018). Key role of bacteria in the short-term cycling of carbon at the abyssal seafloor in a low particulate organic carbon flux region of the eastern Pacific Ocean. *Limnology Oceanography* 64 (2019), 694–713. doi: 10.1002/lno.11069

Talley, L. D., Pickard, G., Emery, W., and Swift, J. (2011). *Descriptive physical oceanography: An introduction* (*6th ed.*). (Boston: Elsevier Academic Press), 560 pp.

Thiel, H.Forschungsverbund Tiefsee-Umweltschutz (2001). Evaluation of the environmental consequences of polymetallic nodule mining based on the results of the TUSCH Research Association. *Deep Sea Res. Part II: Topical Stud. Oceanography* 48 (17-18), 3433–3452. doi: 10.1016/S0967-0645(01)00051-0

Thiel, H., Schriever, G., and Foell, E. J. (2005). Polymetallic nodule mining, waste disposal, and species extinction at the abyssal seafloor. *Mar. Georesources Geotechnology* 23 (3), 209–220. doi: 10.1080/10641190500192292

Tilot, V. (2019). "Assessment of deep-sea faunal communities-indicators of environmental impact," in *Environmental Issues of Deep-Sea Mining. Impacts, Consequences and Policy Perspectives*. Ed. R. Sharma (Cham, Switzerland: Springer Nature Switzerland AG), 145–186.

Uhlenkott, K., Simon-Lledó, E., Vink, A., and Martínez Arbizu, P. (2022). Investigating the benthic megafauna in the eastern Clarion Clipperton Fracture Zone (north-east Pacific) based on distribution models predicted with random forest. *Sci. Rep.* 12, (1). doi: 10.1038/s41598-022-12323-0

Uhlenkott, K., Vink, A., Kuhn, T., Martínez Arbizu, P., and Coleman, M. (2020). Predicting meiofauna abundance to define preservation and impact zones in a deep-sea mining context using random forest modelling. *J. Appl. Ecol.* 57 (7), 1210–1221. doi: 10.1111/1365-2664.13621

van der Grient, J. M. A., and Drazen, J. C. (2021). Potential spatial intersection between high-seas fisheries and deep-sea mining in international waters. *Mar. Policy* 129, 104564. doi: 10.1016/j.marpol.2021.104564

van der Grient, J. M. A., and Drazen, J. C. (2022). Evaluating deep-sea communities' susceptibility to mining plumes using shallow-water data. *Sci. Total Environ.* 852, 158162. doi: 10.1016/j.scitotenv.2022.158162

Van Dover, C. L., Ardron, J. A., Escobar, E., Gianni, M., Gjerde, K. M., Jaeckel, A., et al. (2017). Biodiversity loss from deep-sea mining. *Nat. Geosci.* 10 (7), 464–465. doi: 10.1038/ngeo2983

Van Nijen, K., Van Passel, S., and Squires, D. (2018). A stochastic techno-economic assessment of seabed mining of polymetallic nodules in the Clarion Clipperton Fracture Zone. *Mar. Policy* 95, 133–141. doi: 10.1016/j.marpol.2018.02.027

Vanreusel, A., Hilário, A., Ribeiro, P. A., Menot, L., and Martinez Arbizu, P. (2016). Threatened by mining, polymetallic nodules are required to preserve abyssal epifauna. *Nat. Sci. Rep.* 6, 26808. doi: 10.1038/srep26808

Van Wijk, J. M., and De Hoog, E. (2020). Size reduction of CCZ polymetallic nodules under repeated impact fragmentation. *Results Eng.* 7, 100154. doi: 10.1016/j.rineng.2020.100154

Vare, L. L., Baker, M. C., Howe, J. A., Levin, L. A., Neira, C., Ramirez-Llodra, E. Z., et al. (2018). Scientific considerations for the assessment and management of mine tailings disposal in the deep sea. *Front. Mar. Sci.* 5, (17). doi: 10.3389/fmars.2018.00017

Vecchione, M. (2016). Notes on cephalopods photographed near the bottom in the Clipperton-Clarion Fracture Zone. *Mar. Biodiversity* 47 (2), 307–310. doi: 10.1007/s12526-016-0528-8

Verichev, S., Malukhin, N., Lucieer, P., Drobadenko, V., Vilmis, A., Heeren, J., et al. (2012). "Draft: Assessment of different technologes of vertical hydraulic transport for deep sea mining applications," in *Proceedings of the ASME 2011 31st International Conference on Ocean*, Offshore and Arctic Engineering OMAE2012, Rio de Janeiro, Brazil, June 10-15, 2012. 1–8.

Volkmann, S. (2014) *Deliverable 3.21: Sustainable indicators. Public report submitted to the EU Commission within the 7th Framework Programme (GA No. 604500).* Available at: http://www.bluemining.eu/downloads/.

Volkmann, S. E., and Lehnen, F. (2017). Production key figures for planning the mining of manganese nodules. *Mar. Georesources Geotechnology.* 36 (3), 360–375. doi: 10.1080/1064119X.2017.1319448

Volz, J. B., Geibert, W., Köhler, D., van der Loeff, M. M. R., and Kasten, S. (2023). Alpha radiation from polymetallic nodules and potential health risks from deep-sea mining. *Sci. Rep.* 13, 7895. doi: 10.1038/s41598-023-33971-w

Volz, J. B., Haffert, L., Haeckel, M., Koschinsky, A., and Kasten, S. (2020). Impact of small-scale disturbances on geochemical conditions, biogeochemical processes and element fluxes in surface sediments of the eastern Clarion-Clipperton Zone, Pacific Ocean. *Biogeosciences* 17 (4), 1113–1131. doi: 10.5194/bg-17-1113-2020

Vonnahme, T., Molari, M., Janssen, F., Wenzhöfer, F., Haeckel, M., Titschack, J., et al. (2020). Effects of a deep-sea mining experiment on seafloor microbial communities and functions after 26 years. *Sci. Adv.* 6, eaaz5922. doi: 10.1126/sciadv.aaz5922

Wagner, D., Friedlander, A. M., Pyle, R. L., Brooks, C. M., Gjerde, K. M., and Wilhelm, T. A. (2020). Coral reefs of the high seas: hidden biodiversity hotspots in need of protection. *Front. Mar. Sci.* 7. doi: 10.3389/fmars.2020.567428

Weaver, P. P. E., Aguzzi, J., Boschen-Rose, R. E., Colaço, A., de Stigter, H., Gollner, S., et al. (2022). Assessing plume impacts caused by polymetallic nodule mining vehicles. *Mar. Policy* 139, 105011. doi: 10.1016/j.marpol.2022.105011

Weaver, P. P. E., and Billett, D. (2019). "Environmental impacts of nodule, crust and sulphide mining: an overview," in *Environmental Issues of Deep-Sea Mining. Impacts, Consequences and Policy Perspectives*. Ed. R. Sharma (Cham, Switzerland: Springer Nature Switzerland AG), 27–62.

Wedding, L. M., Green, S. J., Reiter, S., Arrigo, K. R., Hazen, L., Ruckelshaus, M., et al. (2022). Linking multiple stressor science to policy opportunities through network modeling. *Mar. Policy* 146, 105307. doi: 10.1016/j.marpol.2022.105307

Widder, E. A., Robison, B. H., Reisenbichler, K. R., and Haddock, S. H. D. (2005). Using red light for *in situ* observations of deep-sea fishes. *Deep Sea Res. Part I: Oceanographic Res. Papers* 52 (11), 2077–2085. doi: 10.1016/j.dsr.2005.06.007

Williams, R., Erbe, C., Duncan, A., Nielsen, K., Washburn, T., and Smith, C. (2022). Noise from deep-sea mining may span vast ocean areas. *Potential harm is understudied largely overlooked. Sci.* 377 (6602), 157–158. doi: 10.1126/science.abo2804

Wishner, K., Seibel, B. A., Roman, C., Deutsch, C., Outram, D., Shaw, C. T., et al. (2018). Ocean deoxygenation and zooplankton: Very small oxygen differences matter. *Sci. Adv.* 4, eaau5180. doi: 10.1126/sciadv.aau5180

Wu, Y.-H., Liao, L., Wang, C.-S., Ma, W.-L., Meng, F.-X., Wu, M., et al. (2013). A comparison of microbial communities in deep-sea polymetallic nodules and the surrounding sediments in the Pacific Ocean. *Deep Sea Res. Part I: Oceanographic Res. Papers* 79 (0), 40–49. doi: 10.1016/j.dsr.2013.05.004