Marine Policy 114 (2020) 103442

Contents lists available at ScienceDirect

Marine Policy

journal homepage: www.elsevier.com/locate/marpol

Potential effects of deep seabed mining on pelagic and benthopelagic biota

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ARTICLE INFO

Keywords:
Deep seabed mining
Pelagic and benthopelagic communities
Pelagic ecosystem functioning
Anthropogenic impact
ISA
Guidelines

ABSTRACT

Environmental concerns were raised from the very onset of discussions concerning the extraction of metalliferous ores from the deep sea, but most studies have targeted the expected impacts on the benthic communities only. The first section of this study compiles possible impacts of deep seabed mining activities on pelagic organisms. Several processes of mining-related activities were identified that can potentially affect the pelagic environment. Some of these processes will assumedly have only minor effects on the pelagic and benthopelagic communities, for example substrate removal and deposition of material. Most others will severely interfere with pelagic and benthopelagic fauna, at least locally. Some impacts will be directly lethal, but most will impair processes associated with feeding, growth and reproduction, which can ultimately lead to smaller standing stocks, altered communities and loss of biodiversity. The actual scale of effects remains unknown until the pelagic ecosystem is better investigated and the technology becomes specified.

In the second section, the guidance provided by the International Seabed Authority (ISA) for baseline studies, environmental impact assessment (EIA) and monitoring in connection with prospecting and exploration of deep-sea mineral resources is reviewed in the light of potential threats to the pelagic ecosystem. Although the ISA recommendations request assessments not only of benthic, but also of pelagic communities, the recommendations remain unspecific in most cases; possible links between benthic and pelagic communities and their consequences for impact assessments are not considered. Some recommendations for modifications and additions to the existing guidelines are presented.

1. Introduction

The existence of large mineral resources in the deep oceans has been known for decades. Currently five main types of deposits can be distinguished that have some potential for commercial exploitation:

- Ferromanganese (FeMn) nodules, also called polymetallic nodules, occur on abyssal plains and are particularly abundant in the Pacific;
- Seafloor massive sulfides (SMS) form at hydrothermal vents, usually at mid-oceanic ridges and active seamounts;
- Cobalt-rich ferromanganese (FeMn) crusts form at seamounts and slopes on sediment-free substrates, mainly at depths from 800 to 2500 m;
- Metalliferous sediments in brine pools are known only from the central trough of the Red Sea; and
- Phosphorite nodules occur at the upper continental slopes at depths of 200–400 m.

Except for the phosphorites, which are interesting for their phosphate content and potential use in fertilizers, all deposits are rich in valuable metals such as copper, nickel, zinc, cobalt, and gold. Commercial exploitation of such resources, particularly metalliferous sediments and FeMn nodules, was first considered in the 1970s. Due to the technological difficulties of industrial operations at bathyal and abyssal depths and unclear economic feasibility, together with the decline of market prices for the respective minerals, plans for large-scale extraction were never put into practice.

Interest in exploiting mineral deposits in the deep sea has increased in recent years for various reasons, for example rising demand for valuable metals such as cobalt and nickel, and advances in deep-sea technology. In particular, the discovery that the deep-sea deposits also host high concentrations of rare metals, for example tellurium, tungsten, and zirconium that are essential for many advanced technologies [1], and the problem that terrestrial deposits of those resources are often located in a single country or in politically unstable regions, have boosted recent investments in deep seabed mining. The current focus is on SMS and FeMn nodules, but the extraction of FeMn crusts, phosphorites, and metalliferous sediments are also under consideration.

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https://doi.org/10.1016/j.marpol.2019.02.014
Received 5 September 2018; Received in revised form 8 February 2019; Accepted 12 February 2019

However, no commercial exploitation of deep-sea mineral resources has yet been conducted. Technological difficulties and uncertain economic risks are still major obstacles in the commercial utilization of deep-sea mineral deposits.

Environmental concerns were raised from the very onset of discussions concerning the extraction of metalliferous ores from the deep sea [e.g. Ref. [2]]. One early example of an environmental risk assessment was conducted from 1977 to 1981 in conjunction with plans for exploiting metalliferous sediments in the Atlantis II Deep in the central Red Sea (MESEDA) [3]. Other early studies include DOMES, the DISCOL experiment and ATESEPP, all focusing on FeMn nodules in the Pacific [see Ref. [4] for an overview]. In recent years, several international projects have dealt with the environmental effects of deep seabed mining, including the EU-funded project MIDAS [5], the nationally funded EU JPI Oceans pilot action on 'Ecological Aspects of Deep-Sea Mining' and the subsequent 'MiningImpact' project.[1] It has become increasingly clear that deep seabed mining is not possible without also causing severe environmental damage, for example due to a net loss of biodiversity [6].

In 1994, the International Seabed Authority (ISA) was established under the United Nations Convention on the Law of the Sea in order to organize and control human activities on the seafloor in waters outside national jurisdiction ('The Area'). Its tasks include, among others, to develop frameworks for environmental risk assessment and monitoring during prospection, exploration and exploitation of mineral resources in the Area, with the goal to avoid or minimize harm to the environment.

Water column effects resulting from the discharge of surplus sediment ('tailings') during mining activities in the deep sea were already identified in the DOMES project [e.g. Refs. [7–9]] and MESEDA [3,10]. However, the primary focus of these studies was on benthic communities, as the impacts of deep seabed mining on the pelagic realm were considered to be of minor importance. Yet, one particular group, the specialised benthopelagic fauna (i.e. animal communities within several metres of the seafloor) with strong links to the seafloor, has been neglected overall, with the exception of demersal scavengers [e.g. Ref. [11]]. Consequently, the ISA guidance to contractors for environmental impact assessment (EIA) and monitoring, though acknowledging the need for studies in the pelagic environment, focusses strongly on the analysis of benthic communities in the license areas.

This paper reviews possible impacts on the pelagic realm caused by activities in conjunction with deep seabed mining, with a special focus on the benthopelagic fauna. Only deep-water mining of metalliferous resources are considered here, but many principles will also apply to phosphorite mining in shallower waters. The second part of the paper evaluates the current ISA recommendations for the guidance of contractors for the assessment of possible environmental impacts arising from exploration in the light of potential threats to the pelagic fauna, and provides recommendations for modifications of and additions to the existing requirements for exploration and monitoring procedures.

2. Potential impacts of deep seabed mining on pelagic and benthopelagic fauna

This section reviews possible effects of activities in conjunction with deep seabed mining on pelagic and benthopelagic organisms. Normal at-sea operations of support vessels, the usual hazards of shipping and possible accidents are not considered. No full-scale mining test of any metalliferous resource has been performed to date, and thus not all mining effects described are based on direct scientific evidence. Some effects can be inferred from small-scale disturbances or shallow water processes, while others remain speculative. Possible synergistic effects of multiple stressors cannot currently be assessed.

Deep-sea pelagic and benthopelagic communities at bathyal and abyssal depths can be considered to form the largest reservoir of animal diversity on earth [12]. Because the knowledge of deep-water communities and ecosystem functioning is extremely poor [13] and the extent of disturbances from future industrial-scale mining activities is difficult to predict, quantitative assessments of mining impacts, and an overall evaluation whether these will cause "serious harm" [14] to the ecosystem are currently not possible. For example, the benthopelagic community has barely been investigated [15] and is thus probably the least known compartment of the deep-sea realm. On the other hand, this assemblage will likely be affected most by seabed mining activities. The very few existing studies of zooplankton in the near-bottom water layers of the deep sea indicate that a major taxonomic shift occurs close to the seafloor, whereas the communities above some 10 m above bottom (mab) mirror the typical bathy- and abyssopelagic assemblages. This shift could be observed in the abyssal Pacific already between 10 and 50 mab [16], but was reported only below 10 mab in the abyssal Atlantic [15]. In addition to the holoplankton, which spend their whole lifetime in the pelagic realm, meroplanktonic larvae of benthic fauna may substantially increase biodiversity as well as temporal and spatial variability in communities close to the seafloor. Differences in meroplankton composition and abundance were found, for example, between nodule fields in the eastern Clarion-Clipperton Zone (CCZ), ridges and hydrothermal vent fields [17].

The main primary and secondary processes of deep seabed mining activities that can potentially affect the pelagic environment are shown in Fig. 1. In the following, a short description of those processes and how they may impact pelagic communities will be presented. Effects on deep-sea microzooplankton and pelagic microbial communities are not included as only little information [e.g. Ref. [18]] is available for these compartments.

2.1. *Removal of substrate*

The exploitation of all deep-sea mineral deposit types involves the removal of large amounts of substrate. The development of technology is still in the conceptual phase, although full-scale prototypes already exist for SMS deposits. The areas affected by future industrial mining operations of nodules and crusts will be large. FeMn nodules will be collected over areas reaching 100–600 km^2 per year for a single mining operation [19,20], and an area of 260 km^2 was estimated for a FeMn crust mine site with a 20 year duration [21].

Overall, the direct effects of cutting, scraping and raking of ore deposits and their surrounding sediments are probably negligible for pelagic and benthopelagic fauna. However, water jets for loosening material and suction devices for nodules may take up, together with ore, sediment and water, smaller benthopelagic fauna and planktonic larvae which are not capable of avoiding the associated water flow. The overlying brine pools at Red Sea metalliferous sediment deposits, which are most likely to be mined with suction devices, are devoid of fauna. The operation and movement of collectors will, however, induce various indirect effects as discussed below (2.3, 2.4, 2.6), and the destruction and long-term alteration of the benthic fauna caused by the permanent removal of substrate will disrupt links between benthopelagic and benthic communities (see 2.9).

2.2. *Removal of ambient water*

Most mining scenarios currently involve a closed riser system, which uses large amounts of ambient water for diluting the ground or crushed ore and pumping the slurry to the surface, although the use of a continuous line bucket system or collection tanks are other options for transporting the extracted ore to a support vessel. Ambient water may also be used for water jets and suction devices during excavation and pre-processing. Estimates of water removal per single mining operation/collector range from > 40,000 $m^{-3} d^{-1}$ in SMS deposits

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[1] https://miningimpact.geomar.de/home.

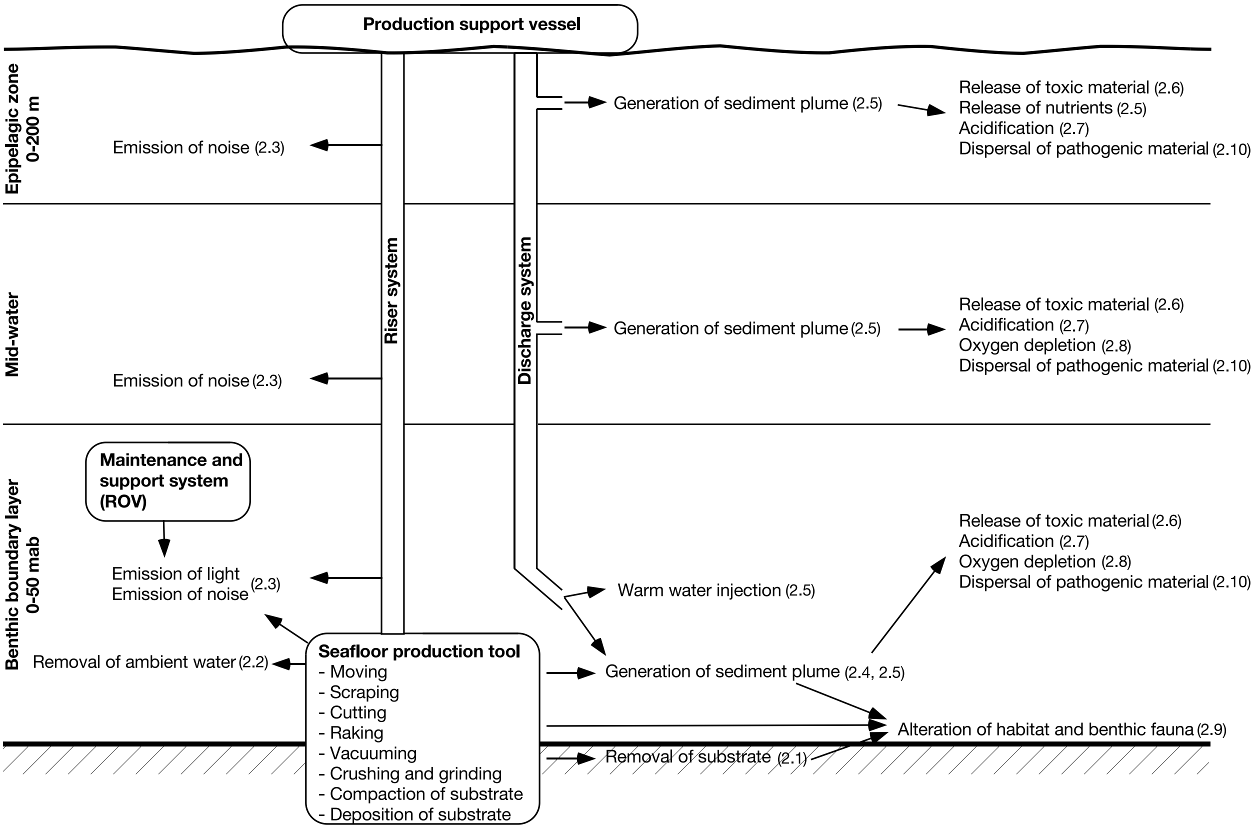

Fig. 1. Graphical representation of the main primary and secondary mining-related processes which potentially interfere with pelagic and benthopelagic biota. Numbers in brackets designate chapters with detailed description.

[22], > 50,000 $m^{-3} d^{-1}$ in FeMn nodule fields [23] and 400,000 $m^{-3} d^{-1}$ in metalliferous sediment of Red Sea brine pools [3]. Although the latter are devoid of fauna [24], the dilution of the slurry may involve water also from outside the brines.

A number of potential impacts from ambient water removal can be expected. Most of the water will likely be taken up from directly above the sea floor (< 10 m). This is the habitat of a specific benthopelagic fauna, including fishes [e.g. Ref. [11]], larger invertebrates [e.g. Refs. [25–27]], and zooplankton, which are substantially different from the overlying water column [e.g. Refs. [15,16]]. Results from the CCZ also indicate an accumulation or retention of meroplanktonic larvae of benthic invertebrates [17] in this layer. The amount of hydraulic entrainment will depend on the inlet diameter and flow velocity of the suction device and vary with the size and mobility of the species. Some of the larger, more mobile fauna may avoid the inlet flow, but information is not available. Evidence from shallow water hydraulic dredging suggests that larger fishes are rarely entrained, whereas larvae and eggs are frequently sucked up [28]. It is, however, questionable whether these results can be transferred to the deep sea, where fishes often appear rather sluggish [29] and may have a lower ability to avoid disturbances than surface-dwelling fishes which live in a naturally turbulent environment [30].

Zooplankton including meroplanktonic larvae will generally be sucked up with the water and killed, as can be inferred from a study by Mullineauxet al. [31] who sampled zooplankton at hydrothermal vent sites using a pump system that had a much lower capacity than anticipated for commercial mining operations. Hydraulic entrainment of meroplankton may be a particular problem for dispersal of benthic fauna at active vent sites, where planktonic larvae of vent invertebrates tend to be concentrated [32].

2.3. *Generation of light and noise*

Collectors for nodules, crusts and SMS will most likely be equipped with strong lights for illuminating the seafloor along the mining path enabling camera control of the operations. Further light emissions will come from remotely operated vehicles (ROVs) used for survey, inspection and maintenance. Underwater noise will be generated at all deposit types by the collector machinery and the riser system close to the bottom, and vibrations and friction in the lift and release pipes may produce sound in mid-water too.

A number of potential impacts can be expected from artificial light emissions. Sunlight does not penetrate deeper than 1000 m into the ocean, and consequently, many deep-sea organisms have partly or completely reduced eyes or light-sensing organs. There are, nonetheless, many fishes and invertebrates with fully developed eyes, which are probably particularly sensitive to the very low light levels of bioluminescence [33]. Bioluminescence is produced by a wide range of organisms spanning from bacteria to fish; it is the only natural light source in the deep sea and a ubiquitous phenomenon in all oceans [34]. Some fishes are known to be attracted to light, whereas others avoid light or do not show any reactions [e.g. Refs. [35–37]]. Attraction to light may enhance the danger of, for example, hydraulic entrainment. The ecological function of bioluminescence will be locally masked by bright illumination. The very 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, Gaten and Shelton [38].

The role of sound in deep-sea ecosystems is still largely unknown, in contrast to the upper water column. It is suggested that deep-sea fishes may use sound for communication [39,40], and mechanoreception is probably important in deep-sea scavengers for the near-field detection of food falls [41]. Some cetaceans dive down to bathyal depths and use sound for echolocation. Since underwater sound propagation, particularly at low frequencies, reaches very far, noise from ore extraction may travel distances of hundreds of kilometres [e.g. Ref. [42]] and impact large areas. Sound propagation is omnidirectional, and therefore is likely to reach the upper water column below the pycnocline or even above, thus having the potential to affect mammals and other marine life not only in deep, but also in surface waters.

Stocker [42] summarises the active and passive use of sound by marine animals, including prey detection, communication, and navigation. Besides directly damaging acoustic sensors or inducing certain behaviour as evident in marine mammals [e.g. Ref. [43]], anthropogenic noise may interfere with the natural use of sound, either by masking biologically relevant sounds, or by triggering false responses [42]. However, since information about sound generation and propagation attributable to deep seabed mining is not available and knowledge about sound perception in deep-sea animals is poor, the likely impacts of noise generation by deep-sea mining tools can currently not be predicted.

2.4. Generation of operational sediment plumes

The operation of the mining tools (raking, cutting, scraping), side cast, pre-processing (grinding, crushing, washing) and the movement of collectors on the seafloor will generate sediment plumes. Such plumes, which comprise inorganic particles and probably some, mostly refractory, organic material, may reach several tens of metres above the seafloor (mab) [9] and are subject to turbulent mixing and dispersal by the near-bottom currents. Deep-reaching mesoscale eddies may enhance particle resuspension and dispersal distance at times [44]. Depending on particle size and associated settling velocity, the suspended material will be re-deposited close to the mining site or at some distance thereof.

There are currently no reliable estimates of the extent of operational sediment plumes at industrial scales with respect to particle concentrations in the water column that may affect zooplankton. Usually, only sedimentation rates, i.e. the benthic footprint, are provided. According to Nautilus Minerals Niugini Limited [45], model simulations calculate the benthic footprint of the sediment plume at the SMS deposit Solwara I to be about 3.5 km^2, with sediment cover ranging from 0.5 m close to the mining pit to < 1 mm at a distance of 700 m. However, these results are disputed by Luick [46] who argues that the area affected and the sediment cover may be larger by one order of magnitude. The mining of FeMn nodules will affect large areas in the range of several hundred km^2 annually [19,20,47]; the extent of the sediment plume and its settling area will be much larger. Modelling of the benthic footprint of the sediment plume generated by a 1 year mining operation at a 12*12 km nodule extraction site indicates a deposition of > 0.1 mm sediment per year up to a distance of 50 km [5]. This rate still exceeds the background sedimentation rate 100fold and does neither include the cumulative effects of multiple and longer term mining operations, nor does it consider the very fine fraction, which is probably most important for zooplankton and which can remain afloat for years [48].

No information is available for FeMn crusts at seamounts. Although the sediment cover at crust sites is generally thin, sediment is present in depressions and crevices and will be resuspended during mining operations. Cutting or scraping of the crusts will also produce sediment clouds. The interactions between steady flow, tidal oscillations and topography will result in complex flow patterns [49], which will make the sphere of influence difficult to predict. Upwelling and turbidity flows will further complicate the scenarios. The operational sediment plumes during mining of metalliferous sediments will probably be very small and not extend beyond the brine pools.

The deep bathyal and the abyssal environments are characterized by very low sedimentation rates in the order of millimetres per 1000 years [50]. Turbidity and particle load are usually very low, but they may increase in the near-bottom water layer due to resuspension, and form a nepheloid layer [51], which was, however, not observed in the CCZ [52].

Information on the feeding ecology of benthopelagic deep-sea fauna, except fishes [see 53 for a review], is poor, but detrivory is supposed to be common in near-bottom zooplankton [e.g. Ref. [54]]. Higher trophic levels rely on benthic or pelagic prey or scavenge on food falls [e.g. Ref. [55]]. The deep sea is generally a food-poor environment which ultimately depends on the energy supply from the epipelagic zone, although chemoautotrophy may locally add to the food supply. Depending on the water depth, the flux of organic matter to the seafloor amounts to < 3% of the export flux [56] and results in a low productivity and small standing stocks of deep-sea organisms, but associated with a high biodiversity [e.g. Ref. [57]].

The particles in the sediment plume cannot contribute to the nutrition of deep-sea fauna because their organic content is lower by nearly two orders of magnitude than in naturally sedimenting particles [58]. On the contrary, the enhanced load of those mostly inorganic particles in the near bottom water layers may directly affect the pelagic and benthopelagic fauna in various ways:

- Burying/smothering is a main concern for benthic organisms, but this effect will probably be minor in the near-bottom pelagic fauna. Some problems could be possible for less mobile benthopelagic animals, such as jellyfish, close to the source, where massive sedimentation occurs, but no information is available.
- High loads of suspended inorganic particles may impair respiration through the clogging of gills, and feeding through clogging the filtration apparatus with unpalatable particles, for example in copepods. Similarly, the mucus nets in flux feeders, for example pteropods, may be clogged by suspended inorganic particles, leading to enhanced weight and sinking speeds and reduced availability of proper food items.
- The competition of unpalatable particles with organic food particles and the ingestion of particles without or with reduced nutritional value [8,59,60] will result in enhanced energy expenditure for feeding and may lead to starvation and reduced growth rates in the near-bottom zooplankton, probably with a cascading effect to higher trophic levels.
- Olfactory is probably the main mechanism for attracting and leading benthopelagic scavengers to food items [e.g. Ref. [61]]. The sediment plumes generated by mining activities will interfere with odour plumes released from food falls, resulting in lower detection rates and generally lower food availability for scavengers.
- Many deep-sea organisms emit light, and this bioluminescence is used, among others, for communication, for example mate finding [e.g. Ref. [62]]. The enhanced turbidity in the sediment plumes will attenuate the light transmission and hence may largely decrease the visibility of light organs, leading to reduced probability of finding a mate and to lower reproduction rates in an environment with extremely low abundances and encounter probabilities for mates.
- Chemosensory is known to be important for mate finding in some shallow-water copepods [63], but it is not known whether chemical cues are used for reproduction also in deep-water animals. A sediment plume would interfere with such chemical trails and lead to decreased reproductive success.

2.5. Generation of discharge sediment plumes

At the extraction sites, the crushed or ground ore will be pumped to a surface support vessel presumably using a hydraulic riser system, or, alternatively, a continuous line bucket system. The hydraulic riser

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[2] The ISA Recommendations are currently (end 2018) under revision, and part of our comments may be obsolete when an updated version is published.

system involves the dilution of the ore with large amounts of water. The resulting slurry must be dewatered on the support vessel and unwanted products ('tailings'), comprising waste water including sediment and fine-grained solids from crushing and abrasion, will be returned to the sea, generating a sediment plume at the release site. Estimates for tailings masses range from 400 t d^{-1} dry solids suspended in about 50,000 t of water per collector associated with FeMn nodule mining [23] to 9,700 t d^{-1} dry solids suspended in 400,000 t of water from metalliferous mud mining [3]. For SMS extraction, Jak et al. [22] assumed a return of 6,000 t d-1 dry solids in 40,000 t of water, but according to Nautilus Minerals Niugini Limited [45] all particles > 8 µm will be retained on the support vessel and disposed of on land, considerably reducing the amount of discharged sediment. The remaining very fine material will, however, settle very slowly and be dispersed over wide areas [48].

The area affected by the discharge sediment plume depends on the duration of the discharge, the amount and grain size distribution of discharged material, the depth of release and the oceanographic conditions. Model simulations suggest that coarse material (> 15 µm) settles rapidly close to the source, whereas fine particles may stay afloat for years and be dispersed over hundreds of kilometres [48]. As in operational plumes, deep-reaching meso-scale eddies may transport waste material over long distances [44]. The effects described above (2.4) for the operational sediment plume are basically applicable also to the discharge plume, but, depending on the depth of release, additional effects may occur:

- Release in the epipelagic zone (0–200 m): Discharged material will stay in the water column for long periods of time and also affect layers below the epipelagic zone. The enhanced turbidity in the photic zone may lead to lower light availability, resulting in significant reduction of primary productivity [7,64], with possible cascading effects to higher trophic levels. Chan and Anderson [7] predicted a 50% reduction of primary production for a full-scale nodule mining operation covering an area of 18 × 2 km, but assumed that this effect would be only temporary due to dilution, advection and settling of particles. At the same time, the discharge of deep-sea water enriched with anorganic nutrients, potentially including iron as micronutrient, in the photic zone may locally increase primary production and alter the composition of the phytoplankton community, for example favouring the development of diatoms. The deep chlorophyll maximum may be lifted to shallower depths. However, long-term and large-scale effects are not anticipated [7]. Nevertheless, a persistent discharge over periods of years would certainly result in long-term effects on the phytoplankton community. The uptake of inorganic particles by zooplankton results in lower growth rates, as described above, but may also induce enhanced particle fluxes due to higher sinking rates of faecal pellets [8]. The discharge current and differences in density between ambient and discharge water may locally induce convection and disrupt stratification of the upper water layer, but possible effects on the ecosystem cannot be predicted.
- Release in the mesopelagic zone (200–1000 m): The presence of vertical migrators is typical for the twilight zone; they forage in surface waters at night and stay at several hundred metres depth during the day. Thus sediment released may be transferred to the epipelagic zone. A marked oxygen minimum zone (OMZ) is present in the mesopelagic zone at low latitudes and may be intensified if oxygen-demanding sediment is released there. Enhanced turbidity due to sediment plumes may reduce the foraging success of visual predators or of predators that attract prey with bioluminescent lures, such as anglerfishes. Communication by bioluminescence may be inhibited. The uptake of inorganic particles by zooplankton may induce higher sinking rates of faecal pellets [8]. Similarly, the sinking velocity of mucus nets may be enhanced. It is not clear, however, whether the resulting enhanced particle flux will be associated with substantially higher organic matter fluxes, which might improve food availability for the deep-sea fauna. Further, it is not clear whether and how the biological and microbial carbon pump might be affected.
- Release in the bathy- and abyssopelagic zones below 1000 m: These zones are completely dark except for bioluminescence. The effects of enhanced particle load will be similar to the zones above, including inhibited ecological function of bioluminescence, but may be more severe because the natural turbidity is extremely low ('clear-water minimum') in these layers, and the competition between sediment particles and natural organic (food) particles is probably substantially stronger than in the zones above, where natural particle abundance is much higher.
- Release close to the bottom: This will affect the smallest area in comparison to the layers above because the settling distance of particles is shortest, but will greatly amplify the impacts of the operational discharge plumes (2.4).

Furthermore, the water used for pumping the ore to the support vessel will be subject to warming in the upper water layers and during processing of the slurry. The release of water with different than ambient temperature may cause, besides physical effects such as turbulence and vertical flows, also direct biological effects. Bathyal and abyssal fauna are generally adapted to low temperatures with very little variation, whereas communities living higher in the water column experience greater temperature variations.

- The release of warmer water in the bathy- and abyssopelagic zones and close to the bottom will most likely impair or even kill the animals subjected to these discharges. It is not known whether more mobile organisms are able to sense and avoid such areas of increased temperatures. Due to rapid mixing with ambient water, the spatial extent of the impact will likely be small.
- The release of cold deep-sea water in the epi- and mesopelagic zones will probably have little direct effect on the communities concerned.
- Injecting large amounts of hot and highly saline brine water from Red Sea mineral sediment deposits probably has a profound effect on the fauna in the vicinity.

2.6. Release of toxic compounds

Both the mining process and the discharge of sediment plumes are associated with the release of potentially toxic substances, for example heavy metals, into the environment. The bioavailability and toxicity of released metals largely depend on environmental conditions. Leaching of heavy metals associated with iron and manganese oxides, as found in FeMn nodules and FeMn crusts, is rather low, but could be greatly enhanced under reducing conditions, for example when tailings are discharged into the OMZ or if anoxic sediment is unearthed [65]. Sulphide-rich ores, as in SMS deposits, '*may leak significant amounts of potentially toxic metals*' [66]. The mining of metalliferous mud in the reducing environment of the Red Sea brine pools would '*constitute a significant influx to the basin*' [3].

Toxic compounds such as heavy metals are known to execute acute or chronic adverse effects on organisms. Such effects have, for example, been shown for mine tailings in shallow water [59,66]. Only limited data are available on the sensitivity of deep-sea fauna to high metal concentrations, for example in deep-sea vent mussels [67]. Naturally enhanced metal concentrations have been found in several deep-sea fishes [68,69], probably indicating reduced sensitivity to metal accumulations in the deep-sea environment. In a review of potentially toxic impacts of metals released during deep seabed mining, Hauton et al. [70] conclude that, considering the influence of temperature, pressure and composition of effluents, reliable predictions of the toxicity on individual organisms are currently not possible. However, the authors propose '*to adopt a Weight of Evidence (WOE) approach to quantify the* *risk associated with mining a particular resource*' [70].

- High concentrations of bioavailable metals released with the operational and discharge plumes into the water column will harm the surrounding communities, resulting, for example, in enhanced mortality, inhibition of growth [71] or lower reproductive rates [72]. Higher trophic levels may be particularly affected due to bioaccumulation in the food chain, and extend the sphere of influence through vertical and horizontal migrations.
- The effect of metal release close to the bottom may be smaller than in the water column if the fauna living there is in fact less sensitive to high metal concentrations, for example at active SMS deposits [45]. This must still be experimentally confirmed.

2.7. Acidification

The mining of SMS has the potential to generate sulphuric acid on the seafloor and in tailings through sulphide mineral oxidation [73]. Experiments indicate that the production of acids from SMS mining does not exceed the buffer capacity of the seawater [73]. It is not clear, however, whether effects of ocean acidification due to climate change may be amplified locally by the release of acid through SMS mining.

2.8. Oxygen depletion

In some oceanic basins, such as the Peru Basin, the depth of oxygenated sediments is shallow [74], and the operation of excavation tools on the seafloor is likely to stir up anoxic sediments. As the bathy- and abyssopelagic water column and the near-bottom water layer are well oxygenated, increased oxygen demand due to the release of anoxic sediments into the water column or the microbial decomposition of dead benthic fauna in the mining path would most likely have negligible effects on the dissolved oxygen concentration in those water layers. However, the release of sediment-laden water containing considerable amounts of anoxic sediment into the OMZ could, at least locally, decrease oxygen concentrations further and lead to anoxia, excluding most zooplankton and micronekton from this layer.

2.9. Alteration of habitat and benthic communities

The removal and intermediate deposition of substrate, the resedimentation of operational and discharge sediment plumes, and the compaction of substrate by mining tools will strongly alter the microtopography and structure of the seafloor at the mining sites of all deposit types. This may also influence the flow characteristic and turbulence in the near-bottom water layer. However, no studies of these issues exist to date. Due to the low natural sedimentation rates, low near-bottom current velocities, and slow reformation of hard substrates such as FeMn nodules and FeMn crusts, that will take millions of years, the changes in the seafloor structure will persist for long periods of time. Although some recolonisation may occur after destruction of the ambient benthic fauna, a long-term alteration of the benthic communities is expected and has been shown in small-scale mining tests [5,75].

Changes in seafloor habitat and the resulting changes in the composition of the benthic communities will also affect the benthopelagic fauna. Most benthic fauna in the path of the mining tool will not survive the mining process. A larger area around the mining site will be affected by operational and discharge sediment plumes, thus partly affecting the benthic animals in the surroundings through smothering or secondary effects. Since the character of the association and interaction between benthopelagic and pelagic fauna and the seafloor is little known, possible impacts remain largely speculative. Even mammals may be concerned, as tracks in nodule bearing areas of the Pacific indicate that whales have interacted with the seafloor even at abyssal depths [76].

- Lebensspuren such as mounds, or other micro-elevations may provide shelter for benthopelagic zooplankton from currents or predators, as suggested for shallow waters [77]. The destruction of such elevations, or the forming of new structures such as tracks and grooves, may differentially influence the behaviour of benthopelagic organisms and alter their species composition.
- The removal of habitat-forming, slow-growing benthic fauna such as corals and sponges will have a long-lasting negative effect on pelagic animals utilising this habitat for food or shelter.
- Altered composition of benthic fauna will affect trophic pathways between benthic and benthopelagic organisms, and thus may favour or discriminate against certain feeding interactions and ultimately change the composition of the benthopelagic communities.
- Benthic suspension feeders are likely to recover only very slowly from mining activities. Suppressed food competition may favour (bentho-)pelagic suspension feeders and increase their abundance.
- Lethal effects of mining on benthic fauna will induce changes in food supply of benthopelagic species and will alter the biodiversity of the pelagic communities through reduced supply of meroplanktonic larvae.
- Species depending on benthic prey, either epifauna or infauna, will experience a local shortage of food. For example, deep-sea fishes can be placed in different feeding guilds [53], and those specialised on benthic food sources may not be able to switch to pelagic prey, which requires completely different feeding strategies. Moving to unaffected areas, if possible, would increase competition with the local fauna for a limited food resource there.
- At hydrothermal vents, numerous trophic interactions between vent fauna and surrounding mobile predators occur [78], which will be interrupted during the mining process and re-established only when rapid recolonisation occurs. This may be possible from nearby active vents in fast-spreading ridge systems with rapid regrowth of chimneys [79], but observations at back-arc systems in the South Pacific showed high stability of vent systems and their associated fauna [80].
- Dead animals associated with the mining activities may provide a short-term enhanced food supply for benthopelagic scavengers, for example lysianassoid amphipods and fishes. It is not clear, however, whether this food source, which will comprise mainly small invertebrates, can be exploited to a large extent by the more mobile and rare scavengers which rely on odour plumes for the detection of food items.

2.10. Introduction of alien species or pathogenic material

All deep-sea mining operations involve the transport of solid material and water from the seafloor to the surface. Principally, this transport will also include animals, microbes and viruses. On the other hand, the release of tailings into the deep sea may transfer surface contaminants into deeper water layers. It is very unlikely that deep-sea eukaryotes would survive the mining process, transport to the support vessel including decompression, and the extremely different environmental conditions in the surface water layers. Similar, it is unlikely that surface contaminants will be able to establish sustainable populations in deep water. However, it cannot be excluded that bacteria, archaea and viruses may remain viable during mining operations and pose a potential health risk to the established communities, but no studies exist addressing this issue.

2.11. Conclusions

This compilation shows that, independent of the fact that only a tiny fraction of the fauna living in the deep-sea pelagic realm is known, many of the processes associated with the mining of deep-sea metalliferous deposits will impact not only the benthic communities but also the pelagic components of the ecosystem, and particularly the

Table 1
Summary of mining-related processes and their potential impact on pelagic (pelagos) and benthopelagic (BBL) biota. Affected deposit types: N (nodules), C (crusts), S (SMS), M (metaliferous sediments).

Process	Direct effects on	Associated processes	Effects on	Location of effects	Area affected	Threat to BBL	Threat to pelagos
Removal of substrate (N, C, S)	Mortality through entrainment	Alteration of habitat and benthic communities Release of toxic compounds	Behaviour Trophic pathways Mortality Growth Reproduction	near seafloor at excavation site	small-large	high	low
Deposition of material (S)	Mortality through burial	Alteration of habitat and benthic communities Release of toxic compounds	Behaviour Trophic pathways Mortality Growth Reproduction	near seafloor at excavation site	small	high	low
Pre-processing of ore at the sea floor (N, C, S)	None	Alteration of habitat and benthic communities Release of toxic compounds	Behaviour Trophic pathways Mortality Growth Reproduction	near seafloor at excavation site	small-medium	high	low
Removal of ambient water (N, C, S, M)	Mortality through entrainment			near seafloor at excavation site	small	locally high	none
Generation of noise and light (N, C, S, M)	Behaviour Mortality through damage of acoustic and light sensors Communication	Enhanced entrainment	Behaviour Mortality Reproduction	near seafloor and in water column	large	high	high
Compacting of bottom substrate (N, C, S)	None	Alteration of habitat and benthic communities	Behaviour Trophic pathways	near seafloor at excavation site	small-medium	high	low
Generation of operational sediment plumes (N, C, S)	Respiration Food availability Odour plumes Communication	Alteration of habitat and benthic communities Release of toxic compounds Acidification	Behaviour Trophic pathways Mortality Growth Reproduction	near seafloor at and around excavation site	medium-large	high	low
Generation of discharge sediment plumes (N, C, S, M)	Respiration Food availability Odour plumes Communication	Alteration of habitat and benthic communities Release of toxic compounds Acidification Oxygen depletion Release of nutrients Injection of water with different than ambient temperature Introduction of alien species or pathogenic material	Behaviour Trophic pathways Mortality Growth Reproduction Primary production	depending on release depth	large	high	high

benthopelagic fauna with its associations to the seafloor (Table 1). Some of the impacts will be directly lethal, but most will impair processes associated with feeding, growth and reproduction, which can ultimately lead to smaller standing stocks, altered communities and loss of biodiversity. However, the scales of potential consequences of these indirect effects for the deep-sea populations, the food web and the overall ecosystem are extremely difficult to verify.

The dispersal capabilities of nekton and zooplankton, including meroplanktonic larvae, are likely relatively high, as compared to the majority of purely benthic fauna [81]. This implies that local losses can rapidly be compensated for by advection from unaffected surrounding waters, given a minimum overall abundance is present, the faunal composition is similar, and suitable habitat is still present. However, composition and biodiversity may be altered if the composition of the communities is not homogeneous over large areas, as reported, for example, for the scavenging fauna of the CCZ [11], or if habitat is destroyed and trophic links to benthic fauna are broken for extended periods. Similarly, the reconstitution of very rare, highly dispersed species may be inhibited, reducing the overall biodiversity. Mobile species may be able to avoid mining effects by moving to unaffected areas but will have to compete there for the limited resources with the local fauna.

Most current scenarios for deep-sea mining activities will assumedly not largely affect the downward flux of organic matter to the deep sea. This means that energy input, except for chemoautotrophic input at SMS sites, will likely remain the same during and after the mining event and that overall productivity should not be altered, or for short periods only. However, long-lasting enhanced particle loads and inorganic/organic particle ratios, as well as the changes in the benthic communities, which will be persistent for very long periods in most cases [e.g. Refs. [5,6,82,83]], will affect food availability and trophic pathways and thus induce long-term alterations in the composition of the benthopelagic and eventually pelagic communities and food webs as well.

Because the knowledge of life history traits, zoogeographic distribution and connectivity of deep-sea pelagic and particularly benthopelagic zooplankton is extremely poor and the dimensions and technology of the planned mining operations are still under discussion, it is currently not possible to predict whether the consequences of deep seabed mining for these compartments will be locally and temporally restricted, or whether they will be persistent and affect larger regions. It can, however, be anticipated that large-scale and persistent changes in the bottom communities will also lead to long-term altered near-bottom pelagic fauna in the areas affected, which may add to pressures on these ecosystems caused by ocean warming and acidification.

3. ISA recommendations with significance for pelagic ecosystems[2]

Currently, the ISA provides regulations and recommendations only for environmental baseline studies, the conduct of environmental impact assessments (EIA) and monitoring in connection with prospecting and exploration of deep-sea mineral resources in the Area [84]. No such guidance is yet available for the exploitation phase, although these regulations are being developed with the overall aim to have them in place within the next few years. Whereas the 'Regulations on Prospecting and Exploration' [[84], Part I] include only very general obligations for the contractors with respect to environmental studies, some more specific guidelines are given in the 'Recommendations and Procedures' issued by the Legal and Technical Committee (LTC), particularly in documents ISBA/19/LTC/8 and ISBA/21/LTC/15 [[84], Part II]. In the following, these regulations and recommendations are reviewed with respect to the guidance given on baseline investigations and impact monitoring of the pelagic ecosystem (3.1 and 3.2), and some recommendations for modifications and additions to the existing guidelines are provided (3.3).

3.1. Review of recommendations for the guidance of contractors for the assessment of the possible environmental impacts arising from exploration for marine minerals in the area (ISBA/19/LTC/8)

The recommendations provided by the ISA LTC in ISBA/19/LTC/8 [84] describe the procedures to be followed by exploration contractors for the acquisition of baseline data, and the monitoring to be performed during and after any activity that is potentially harmful to the environment. It specifies that each Plan of Work, the basis of each exploration contract, requires environmental baseline studies, monitoring of the possible effects of the work on the environment and particular monitoring during and after testing of collecting systems and equipment.

Part III of ISBA/19/LTC/8 lists baseline data requirements from physical and chemical oceanography, geology, sediment properties and biological communities. Recommendation #15e requires to '*Assess pelagic communities in the water column and in the benthic boundary layer that may be impacted by operations (*e.g. *the operational and discharge plumes)*' (#15e-iii), to '*Record sightings of marine mammals, other near-surface large animals (such as turtles and fish schools) and bird aggregations'* (#15e-v), and to '*Establish at least one station within each habitat type or region, as appropriate, to evaluate temporal variations in water column and seabed communities*' (#15e-vi). No further specifications are given. Although variability of the environment is explicitly named, no scales are indicated, and it is not clear how temporal variability can be assessed by placing singular sampling stations at different habitats, as recommended in #15e-vi. No trophic or other process studies are required. Methodological aspects are not addressed, although being essential for the quality and comparability of data.

The explanatory comments in Annex 1 to ISBA/19/LTC/8 [84] provide some more specific explanations on data to be collected. Comments #23 and #24 point out that data shall be collected '*on natural communities … to evaluate the potential effect of the activities on the benthic and pelagic fauna*' and that pelagic and benthic communities should be characterized '*within all subhabitats that may be impacted by mining operations and to determine the regional distributions …* '. The need to gain information on spatial variation in the biological community is addressed in comment #33, but possible differences in the scales of variability between benthic and pelagic communities are not considered.

Comments #36 and #37 give advice on which data are to be collected, and include some methodological aspects. Comment #36 deals with benthic communities, but includes also demersal scavengers. Whereas time-lapse baited cameras should address the activity level of megafauna, baited traps '*may be used to characterize the community species composition*'. For necrophagous amphipods short-term deployments of 24–48 h are suggested; no soak times are given for other scavengers. No quantitative assessments of scavengers are demanded. Demersal fishes are not specifically named.

The work to be done on plankton communities is laid down in comment #37. The plankton communities of the upper 200 m should be characterized '*if there is potential for surface discharge*', but, depending on the plume modelling, the need to study plankton communities over a wide depth range and particularly around the discharge depth and below, including the BBL community, is acknowledged. The main focus lies on the structure and (primary) production of the plankton communities, whereas, for example, micronekton, nekton, vertical migrations, the possible influence of OMZs, and food web structure and dynamics are not considered.

Comment #38 deals with trace metals and potentially toxic elements, primarily in demersal fishes and invertebrates. Assessments of potential ecotoxicological impacts on phytoplankton and zooplankton are considered necessary only if the discharge plume is released at the surface or in mid-water.

Part IV of ISBA/19/LTC/8 addresses, in general terms, the framework for activities that require an EIA, for example, testing of collection systems and equipment. Recommendation #22 assumes that the main impact will be at the seafloor, but that the '*impact assessment should address impacts on benthic, benthic boundary layer and pelagic environments*', considering not only the areas directly affected, but also the wider region impacted by operational and discharge plumes and material released by transporting to the surface. In addition, EIAs are required for discharge plumes at the surface because '*environmental changes may alter food chains, disturb vertical and other migrations and lead to changes in the geochemistry of an oxygen-minimum zone, if present'* (#25). However, no specific requirements for these EIAs are given.

The guidance on observations and measurements to be made while performing a specific activity (Part IV-D) do not include biological information, but are important as they describe the main characteristics of the activity, which may directly affect the biological communities, for example, the '*chemical and physical characteristics of the discharge, behaviour of the discharged plume … '* (#29). Direct biological measurements are designated only after the activity (Part IV-E), here assuming that testing activities are of short duration. Although recommendation #30 addresses mostly benthic communities, '*changes in the behaviour of the fauna at and below the discharge plume*' are also considered. It is, however, not clear what is meant with changes in behaviour, and how this should be assessed. Ecotoxicological measurements shall be made with benthic organisms, however not with pelagic fauna (but see comment #38 in Annex 1), nor are tests of any kind forseen to study the tolerance of pelagic fauna to enhanced particle loads. Additional specific requirements are given for SMS and FeMn crust deposits (Part IV-F), but address nearly exclusively benthic communities, although mining activities at these sites will certainly also affect pelagic biota. Only at seamounts the need to assess '*demersal fish and other nekton living over the sea floor*' is acknowledged, ignoring the other pelagic compartments.

3.2. Review of recommendations for the guidance of contractors on the content, format and structure of annual reports (ISBA/21/LTC/15)

The annual reports of contractors, as laid out in ISBA/21/LTC/15 [84], have to provide not only general *'information on biological communities and biodiversity studies*', including demersal scavengers and pelagic communities, but also information on ecosystem functioning. The latter includes bioturbation, stable isotopes and sediment community oxygen consumption for FeMn nodules communities, food webs, stable isotopes, fatty acids and methane and hydrogen sulphide metabolism in SMS communities, and food webs, stable isotopes and fatty acids in FeMn crust communities. Because food web studies are not required for pelagic communities in ISBA/19/LTC/8 [84], it is not clear whether reports on ecosystem functioning are supposed to include pelagic communities. In addition, food web studies are suggested only for SMS and FeMn crust deposits, although they are essential for understanding ecosystem functioning in nodule fields as well.

Measurements of metabolic rates are not requested at all.

3.3. Recommendations for amendment

Generally, the ISA recommendations for baseline and monitoring studies during prospection and exploration request assessments not only of benthic, but also of pelagic communities. However, the recommendations remain unspecific in most cases. With a few exceptions, neither the target groups and parameters to be measured nor methodological aspects are mentioned, although it is acknowledged in ISBA/19/LTC/8 recommendation #17 that '*The best available technology and methodology for sampling should be used in establishing baseline data for environmental impact assessments*' and in comment #32 of Annex 1 that '*Standardization of methodology and reporting is extremely important*' [84]. It has to be made clear that standardization is necessary not only within assessments of one operator, but across all operators in order to establish regional baselines. No mention is made of possible links between benthic and pelagic communities and their consequences for impact assessments. Study design concepts for the different deposit types are lacking. Although in recommendation #26 of ISBA/19/LTC/8 [84] contractors are obliged to delineate impact reference areas which should be '*representative of the site to be mined in terms of environmental characteristics and biota*' and will be '*important in identifying natural variations in environmental conditions',* no information is provided on the character and frequency of possible investigations in these areas. So far, the criteria proposed by an expert workshop for the selection of such sites do not explicitly include water column and pelagic fauna characteristics, but the recommended monitoring of the sites does include the study of effects on the pelagic community [85].

Whereas a detailed concept for the study of pelagic communities in the framework of deep seabed mining is beyond the scope of this report, some recommendations for a meaningful standardized assessment and monitoring programme of the pelagic components of the ecosystem potentially affected by deep seabed mining are provided here. Pelagic microbial communities are not considered here, although it is evident that they are an important component of the deep-sea ecosystem. In our view, studies on pelagic communities should pursue two main goals: 1. to better understand the deep-sea ecosystem in order to facilitate meaningful predictions of the potential impacts of disturbances, for example, through modelling, and 2. to detect possible changes in ecosystem structure caused by the industrial activities, for example in biodiversity, standing stocks and functional relationships.

In the following, after some general design considerations, three hierarchical scenarios are distinguished, depending on the release depth of the discharge sediment plume. The first scenario includes basic assessments required for the mining operations and also covers a discharge of tailings close to the seafloor. The other two scenarios address additional requirements if the tailings are discharged higher up in the water column.

3.3.1. General design considerations

Baseline studies prior to an experimental disturbance and monitoring studies after the disturbance should principally follow the same design. Monitoring of the disturbance and assessments of the effects should be made immediately after the disturbance, and then in regular intervals until there is experience as to the persistence of changes in the pelagic environment. The sampling grid should be designed to represent (a) the main abiotic and biotic features of the mining site, (b) at least three locations representing maximum, medium and minimum particle concentrations in operational and discharge plumes, (c) one or more reference stations outside the area affected. A sufficient number of replicates at each station are necessary to allow for robust statistical analyses, and repeated (e.g., seasonal) measurements are desirable to account for natural temporal variability. All biological measurements should be accompanied by environmental assessments, such as profiles of the physical and chemical properties of the water column. A standardization of methods is essential; for an overview of recommended biological sampling methods in the deep sea, including the pelagic and benthopelagic fauna, see Clark, Consalvey and Rowden [86].

3.3.2. Scenario 1: discharge close to the seafloor (within ca. 50 mab)

The following assessments would be required at all stations, if not stated otherwise:

- Occurrence of marine mammals (visual, acoustic) and background noise levels.
- Composition, abundance and biomass of zooplankton (10, 50, 100 mab). Methods: Multiple opening/closing nets and imaging systems (e.g., video plankton recorder).
- Composition, abundance and biomass of BBL zooplankton (ca. 1 mab). Methods: Multiple opening/closing nets in combination with epibenthic sledge or/and ROV, and imaging systems (e.g., video plankton recorder) in combination with ROV or AUV.
- Composition, abundance and biomass of BBL and near-bottom (up to 100 mab) nekton (fishes and invertebrates). Methods: Trawls (preferably with closing system), imaging and acoustic systems (e.g., in combination with ROV or AUV), moored baited cameras and traps, long-term deployment (> 1 year) of time-lapse camera and multifrequency sounder.
- Additional measurements for food web analysis in the affected water layers: Stomach contents in fishes and larger invertebrates, where applicable; stable isotope ratios ($\delta^{15}N$, $\delta^{13}C$), fatty acid biomarkers and enzymatic activity (e.g., ETS) in key species from all size groups and trophic levels and including benthic fauna and POM; identification of feeding types. *In situ* experiments measuring community metabolism (e.g., oxygen consumption) and effects of enhanced (inorganic) particle concentrations on suspension feeders at one station would be desirable.
- Additional measurements for toxicology: Concentrations of heavy metals in tissue of fishes and invertebrates. *In situ* experiments for effects of enhanced metal exposure to species of different trophic levels would be desirable at one station.

3.3.3. Scenario 2: discharge in the water column below the epipelagic zone

In addition to Scenario 1, the following measurements are required if the discharge plume is released into the water column.:

- Depth-stratified assessment of composition, abundance and biomass of zooplankton in the water column at and below the discharge depth (down to the bottom) at the reference site, the release location and at least three locations along the dilution gradient of the plume, as calculated from plume dispersal modelling. If vertical convection or vertical migrations are to be expected, the water column above the discharge depth should also be considered. Methods: Multiple opening/closing nets and imaging systems (e.g., video plankton recorder or underwater vision profiler).
- Depth-stratified assessment of composition, abundance and biomass of micronekton and nekton in the water column at and below the discharge depth (down to the bottom) at the stations as above. If vertical convection or vertical migrations are to be expected, the water column above the discharge depth should also be considered. Methods: Multiple opening/closing pelagic trawls and multi-frequency hydroacoustics.
- If the mesopelagic zone is affected, diel vertical migrations (DVM) should be considered and day and night samples performed. Special attention should be paid to the OMZ, if present.

3.3.4. Scenario 3: discharge in the epipelagic zone

This scenario requires additional assessments in the epipelagic zone:

- Depth-stratified assessment of Chl. a, primary production,

phytoplankton size spectra and taxonomic composition at the reference site, the release location and at least three locations along the dilution gradient of the plume, as calculated from plume dispersal modelling. Methods: fluorometer, in vitro primary production measurements and/or FastTracka®, cytometry, HPLC.
- Depth-stratified assessment of composition, abundance and biomass of zooplankton in the epipelagic zone, considering DVM. Stations as above. Methods: Multiple opening/closing nets and imaging systems (e.g., video plankton recorder or underwater vision profiler).
- Depth-stratified assessment of composition, abundance and biomass of micronekton and nekton in the epipelagic zone, considering DVM. Stations as above. Methods: Multiple opening/closing pelagic trawls and multifrequency hydroacoustics.

3.3.5. Additional special requirements at SMS and FeMn crust sites

The often rugged topography at vents and seamounts makes the assessment of near-bottom fauna challenging. Particularly seamounts feature variable habitat and water depths over short distances. The interaction between seamount topography and currents induces complex flow patterns, which may result in high temporal and spatial variability of pelagic fauna. FeMn crust deposits and the resulting sediment plumes from mining activities may lie within the range of diel vertical migrators, and possible effects on the surface communities, including fishes important for human consumption, have to be considered.

- At sites with rough bottom topography and at active vents, the zooplankton community close to the seafloor should be assessed with ROVs and/or terrain-following autonomous underwater vehicles (AUVs) equipped with closing nets and imaging systems. Pumps may be useful if abundances are sufficiently high. No large trawls should be used to assess benthopelagic nekton, but in addition to optical and acoustic systems and baited traps, small epibenthic sledges specifically designed for rough bottom could be employed.
- The sampling grid has to consider the small-scale variations in habitat and hydrographic conditions.
- The temporal variability encountered at seamounts and active vents, for example episodic larval release, should be monitored with moored long-term (at least one year) recording systems using imaging and multifrequency hydroacoustics.

4. Outlook

All scenarios described in section 2 and the recommendations given in section 3 consider only local effects of deep seabed mining activities, although the areas affected may be very large. In order to assess the possible global implications, for example a general loss of biodiversity, much better knowledge of the deep-sea ecosystems and their pelagic compartments is necessary. Research activities, including those carried out in the framework of exploration programmes and testing activities, can contribute to increasing our understanding of pelagic communities in the deep-sea realm (e.g. species distributions, ecosystem functioning), but, given the sheer vastness of the deep sea, the sampling effort will be tremendous. Until then, the precautionary principle should be rigorously applied to deep seabed mining activities.

Acknowledgements

We would like to thank two anonymous reviewers for their comments, which helped to improve the manuscript substantially. AD was supported by IASS through a grant to Universität Hamburg (Contract No. D-W/D-51160-17-17). The Umweltbundesamt (UBA) funded SC through a grant to IASS.

References

[1] J.R. Hein, K. Mizell, A. Koschinsky, T.A. Conrad, Deep-ocean mineral deposits as a source of critical metals for high- and green-technology applications: comparison with land-based resources, Ore Geol. Rev. 51 (0) (2013) 1–14, https://doi.org/10.1016/j.oregeorev.2012.12.001.

[2] A.F. Amos, O.A. Roels, Environmental aspects of manganese nodule mining, Mar. Pol. 1 (2) (1977) 156–163, https://doi.org/10.1016/0308-597X(77)90050-1.

[3] H. Thiel, L. Karbe, H. Weikert, Environmental risks of mining metalliferous muds in the Atlantis II deep, Red Sea, in: N.M.A. Rasul, I.C.F. Stewart (Eds.), The Red Sea, Springer-Verlag, Berlin, Heidelberg, 2015, pp. 251–266.

[4] H. Thiel, Use and protection of the deep sea—an introduction, Deep Sea Res. Part II Top. Stud. Oceanogr. 48 (17) (2001) 3427–3431, https://doi.org/10.1016/S0967-0645(01)00050-9.

[5] MIDAS Consortium, The MIDAS Project: Research Highlights, (2016) https://www.eu-midas.net/sites/default/files/downloads/MIDAS_research_highlights_low_res.pdf.

[6] H.J. Niner, J.A. Ardron, E.G. Escobar, M. Gianni, A. Jaeckel, D.O.B. Jones, L.A. Levin, C.R. Smith, T. Thiele, P.J. Turner, C.L.V. Dover, L. Watling, K.M. Gjerde, Deep-sea mining with no net loss of biodiversity—an impossible aim, Frontiers in Marine Science 5 (2018), https://doi.org/10.3389/fmars.2018.00053.

[7] A.T. Chan, G.C. Anderson, Environmental investigation of the effects of deep-sea mining on marine phytoplankton and primary productivity in the tropical Eastern North Pacific Ocean, Mar. Min. 3 (½) (1981) 121–149.

[8] J. Hirota, Potential effects of deep-sea minerals mining on macrozooplankton in the North Equatorial Pacific, Mar. Min. 3 (12) (1981) 19–57.

[9] E. Ozturgut, J.W. Lavelle, R.E. Burns, Chapter 15 impacts of manganese nodule mining on the environment: results from pilot-scale mining tests in the north equatorial pacific, in: R.A. Geyer (Ed.), Elsevier Oceanography Series, Elsevier, 1981, pp. 437–474.

[10] Y.B. Abu Gideiri, Impacts of mining on central Red Sea environment, deep sea research Part A, Oceanographic Research Papers 31 (6–8) (1984) 823–828, https://doi.org/10.1016/0198-0149(84)90042-6.

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

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

[13] B.H. Robison, Deep pelagic biology, J. Exp. Mar. Biol. Ecol. 300 (1–2) (2004) 253–272, https://doi.org/10.1016/j.jembe.2004.01.012.

[14] L.A. Levin, K. Mengerink, K.M. Gjerde, A.A. Rowden, C.L. Van Dover, M.R. Clark, E. Ramirez-Llodra, B. Currie, C.R. Smith, K.N. Sato, N. Gallo, A.K. Sweetman, H. Lily, C.W. Armstrong, J. Brider, Defining "serious harm" to the marine environment in the context of deep-seabed mining, Mar. Pol. 74 (2016) 245–259, https://doi.org/10.1016/j.marpol.2016.09.032.

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

[16] K.F. Wishner, Aspects of the community ecology of deep-sea, benthopelagic plankton, with special attention to gymnopleid copepods, Mar. Biol. 60 (1980) 179–187, https://doi.org/10.1007/BF00389161.

[17] O. Kersten, C.R. Smith, E.W. Vetter, Abyssal near-bottom dispersal stages of benthic invertebrates in the Clarion-Clipperton polymetallic nodule province, Deep-Sea Res. I 127 (2017) 31–40, https://doi.org/10.1016/j.dsr.2017.07.001.

[18] M.V. Lindh, B.M. Maillot, C.N. Shulse, A.J. Gooday, D.J. Amon, C.R. Smith, M.J. Church, From the surface to the deep-sea: bacterial distributions across polymetallic nodule fields in the clarion-clipperton zone of the pacific ocean, Front. Microbiol. 8 (2017) 1696, https://doi.org/10.3389/fmicb.2017.01696.

[19] R. Sharma, Environmental issues of deep-sea mining, Procedia Earth and Planetary Science 11 (2015) 204–211, https://doi.org/10.1016/j.proeps.2015.06.026.

[20] S.E. Volkmann, F. Lehnen, Production key figures for planning the mining of manganese nodules, Mar. Georesour. Geotechnol. (2017) 1–16, https://doi.org/10.1080/1064119X.2017.1319448.

[21] J.R. Hein, T.A. Conrad, R.E. Dunham, Seamount characteristics and mine-site model applied to exploration- and mining-lease-block selection for cobalt-rich ferromanganese crusts, Mar. Georesour. Geotechnol. 27 (2) (2009) 160–176, https://doi.org/10.1080/10641190902852485.

[22] R. Jak, S. Lagerveld, P. de Vries, L. de Wit, C. van Rhee, G. Duineveld, M. Lavaleye, M. Huisman, M. Nijhof, S. von Benda-Beckmann, S. Steenbrink, G. van Raalte, W. Boomsma, A. Ortega, S. Verichev, M. Campman, R. Haddorp, Towards Zero Impact of Deep Sea Offshore Projects, Delft University of Technology, Delft, 2014.

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

[24] S. Kaartvedt, A. Antunes, A. Røstad, T.A. Klevjer, H. Vestheim, Zooplankton at deep Red Sea brine pools, J. Plankton Res. 38 (3) (2016) 679–684, https://doi.org/10.1093/plankt/fbw013.

[25] M.H. Thurston, Abyssal necrophagous amphipods (Crustacea: Amphipoda) in the northeast and tropical Atlantic Ocean, Prog. Oceanogr. 24 (1990) 257–274.

[26] A.L. Vereshchaka, Macroplankton in the near-bottom layer of continental slopes and seamounts, Deep-Sea Res. I 42 (9) (1995) 1639–1668.

[27] M. Vecchione, Notes on cephalopods photographed near the bottom in the

Clipperton-Clarion Fracture Zone, Mar. Biodivers. 47 (2) (2017) 307–310, https://doi.org/10.1007/s12526-016-0528-8.

[28] A.S. Wenger, E. Harvey, S. Wilson, C. Rawson, S.J. Newman, D. Clarke, B.J. Saunders, N. Browne, M.J. Travers, J.L. Mcilwain, P.L.A. Erftemeijer, J.-P.A. Hobbs, D. Mclean, M. Depczynski, R.D. Evans, A Critical Analysis of the Direct Effects of Dredging on Fish, Fish and Fisheries, 2017, pp. 1–19, https://doi.org/10.1111/faf.12218.

[29] J.A. Koslow, Energetic and life-history patterns of deep-sea benthic, benthopelagic and seamount-associated fish, J. Fish. Biol. 49 (Suppl. A) (1996) 54–74, https://doi.org/10.1111/j.1095-8649.1996.tb06067.x.

[30] T.D. Linley, C.H.S. Alt, D.O.B. Jones, I.G. Priede, Bathyal demersal fishes of charlie gibbs fracture zone region (49°-54°N) of the mid-atlantic ridge: III. Results from remotely operated vehicle (ROV) video transects, Deep Sea Res. Part II Top. Stud. Oceanogr. 98 (2013) 407–411, https://doi.org/10.1016/j.dsr2.2013.08.013.

[31] L.S. Mullineaux, S.W. Mills, A.K. Sweetman, A.H. Beaudreau, A. Metaxas, H.L. Hunt, Vertical, lateral and temporal structure in larval distributions at hydrothermal vents, Mar. Ecol. Prog. Ser. 293 (2005) 1–16, https://doi.org/10.3354/meps293001.

[32] C.L. Van Dover, Impacts of anthropogenic disturbances at deep-sea hydrothermal vent ecosystems: a review, Mar. Environ. Res. 102 (2014) 59–72, https://doi.org/10.1016/j.marenvres.2014.03.008.

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

[34] S.H.D. Haddock, M.A. Moline, J.F. Case, Bioluminescence in the sea, Annual Review of Marine Science 2 (2010) 443–493, https://doi.org/10.1146/annurev-marine-120308-081028.

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

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

[37] E.A. Widder, Bioluminescence in the ocean: origins of biological, chemical, and ecological diversity, Science 328 (5979) (2010) 704–708, https://doi.org/10.1126/science.1174269.

[38] P.J. Herring, E. Gaten, P.M.J. Shelton, Are vent shrimps blinded by science? Nature 398 (6723) (1999), https://doi.org/10.1038/18142 116-116.

[39] R. Rountree, F. Juanes, C. Goudey, K. Ekstrom, Is biological sound production important in the deep sea? in: A. Popper, A. Hawkins (Eds.), The Effects of Noise on Aquatic Life, Springer, 2011, pp. 181–183.

[40] C.C. Wall, R.A. Rountree, C. Pomerleau, F. Juanes, An exploration for deep-sea fish sounds off Vancouver Island from the NEPTUNE Canada ocean observing system, Deep-Sea Res. I 83 (2014) 57–64, https://doi.org/10.1016/j.dsr.2013.09.004.

[41] M. Klages, S. Muyakshin, T. Soltwedel, W.E. Arntz, Mechanoreception, a possible mechanism for food fall detection in deep-sea scavengers, Deep-Sea Res. I 49 (1) (2002) 143–155, https://doi.org/10.1016/S0967-0637(01)00047-4.

[42] M. Stocker, 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 (2002) 2431–2457, https://doi.org/10.1121/1.4779979.

[43] R. Kastelein, N. Jennings, Impacts of anthropogenic sounds on phocoena phocoena (Harbor porpoise), in: A.N. Popper, A. Hawkins (Eds.), The Effects of Noise on Aquatic Life, Springer New York, New York, NY, 2012, pp. 311–315.

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

[45] Nautilus Minerals Niugini Limited, Environmental Impact Statement Solwara 1 Project, Coffey Natural Systems, Brisbane, Australia, 2008.

[46] J.L. Luick, Physical Oceanographic Assessment of the Nautilus EIS for the Solwara I Project, Deep Sea Mining Campaign, 2012, p. 26.

[47] E. Ozturgut, J.W. Lavelle, The influence of the pycnocline on the oceanic settling of manganese nodule mining waste, Mar. Environ. Res. 12 (2) (1984) 127–142, https://doi.org/10.1016/0141-1136(84)90018-7.

[48] S. Rolinski, J. Segschneider, J. Sündermann, Long-term propagation of tailings from deep-sea mining under variable conditions by means of numerical simulations, Deep Sea Res. Part II Top. Stud. Oceanogr. 48 (17) (2001) 3469–3485, https://doi.org/10.1016/S0967-0645(01)00053-4.

[49] J.W. Lavelle, C. Mohn, Motion, commotion, and biophysical connections at deep ocean seamounts, Oceanography 23 (1) (2010) 90–103.

[50] A. Glover, C.R. Smith, The deep seafloor ecosystem: current status and prospects for change by 2025, Environ. Conserv. 30 (3) (2003) 1–23, https://doi.org/10.1017/S0376892903000225.

[51] F. Nyffeler, C.-H. Godet, The structural parameters of the benthic nepheloid layer in the northeast Atlantic, Deep-Sea Res. 33 (2) (1986) 195–207, https://doi.org/10.1016/0198-0149(86)90118-4.

[52] I.T. Lipton, M.J. Nimmo, J.M. Parianos, NI 43-101 Technical Report TOML Clarion Clipperton Zone Project, Pacific Ocean, AMC Consultants Pty Ltd., Brisbane, 2016, p. 279.

[53] J.C. Drazen, T.T. Sutton, Dining in the deep: the feeding ecology of deep-sea fishes, Ann. Rev. Mar. Sci. 9 (2017) 337–366, https://doi.org/10.1146/annurev-marine-010816-060543.

[54] A. Denda, B. Stefanowitsch, B. Christiansen, From the epipelagic zone to the abyss: trophic structure at two seamounts in the subtropical and tropical Eastern Atlantic - Part I zooplankton and micronekton, Deep-Sea Res. I 130 (2017) 63–77, https://doi.org/10.1016/j.dsr.2017.10.010.

[55] A. Denda, B. Stefanowitsch, B. Christiansen, From the epipelagic zone to the abyss: trophic structure at two seamounts in the subtropical and tropical Eastern Atlantic - Part II Benthopelagic fishes, Deep-Sea Res. I 130 (2017) 78–92, https://doi.org/10.1016/j.dsr.2017.08.005.

[56] J.T. Turner, Zooplankton fecal pellets, marine snow, phytodetritus and the ocean's biological pump, Prog. Oceanogr. 130 (0) (2015) 205–248, https://doi.org/10.1016/j.pocean.2014.08.005.

[57] D.J. Amon, A.F. Ziegler, T.G. Dahlgren, A.G. Glover, A. Goineau, A.J. Gooday, H. Wiklund, C.R. Smith, Insights into the abundance and diversity of abyssal megafauna in a polymetallic-nodule region in the eastern Clarion-Clipperton Zone, Sci. Rep. 6 (2016) 30492, https://doi.org/10.1038/srep30492.

[58] H.J. Kim, D. Kim, K. Hyeong, J. Hwang, C.M. Yoo, D.J. Ham, I. Seo, Evaluation of resuspended sediments to sinking particles by benthic disturbance in the clarion-clipperton nodule fields, Mar. Georesour. Geotechnol. 33 (2) (2014) 160–166, https://doi.org/10.1080/1064119x.2013.815675.

[59] E.P. Anderson, D.L. Mackas, Lethal and sublethal effects of a molybdenum mine tailing on marine zooplankton: mortality, respiration, feeding and swimming behavior in *Calanus marshallae, Metridia pacifica* and *Euphausia pacifica*, Mar. Environ. Res. 19 (2) (1986) 131–155, https://doi.org/10.1016/0141-1136(86)90043-7.

[60] V.J.H. Hu, Ingestion of deep-sea mining discharge by five species of tropical copepods, Water Air Soil Pollut. 15 (4) (1981) 433–440, https://doi.org/10.1007/bf00279425.

[61] B. Sainte-Marie, Foraging of scavenging deep-sea lysianassoid amphipods, in: G.T. Rowe, V. Pariente (Eds.), Deep-sea Food Chains and the Global Carbon Cycle, NATO ASI Series, Kluwer Academic Publishers, Dordrecht, 1992, pp. 105–124.

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

[63] T. Kiørboe, E. Bagøien, Motility patterns and mate encounter rates in planktonic copepods, Limnol. Oceanogr. 50 (6) (2005) 1999–2007, https://doi.org/10.4319/lo.2005.50.6.1999.

[64] J.H. Hyun, K.H. Kim, H.S. Jung, K.Y. Lee, Potential environmental impact of deep seabed manganese nodule mining on the *Synechococcus* (cyanobacteria) in the northeast equatorial Pacific: effect of bottom water-sediment slurry, Mar. Georesour. Geotechnol. 16 (2) (1998) 133–143, https://doi.org/10.1080/10641199809379963.

[65] A. Koschinsky, U. Fritsche, A. Winkler, Sequential leaching of Peru Basin surface sediment for the assessment of aged and fresh heavy metal associations and mobility, Deep Sea Res. Part II Top. Stud. Oceanogr. 48 (17) (2001) 3683–3699, https://doi.org/10.1016/S0967-0645(01)00062-5.

[66] E. Ramirez-Llodra, H.C. Trannum, A. Evenset, L.A. Levin, M. Andersson, T.E. Finne, A. Hilario, B. Flem, G. Christensen, M. Schaanning, A. Vanreusel, 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) (2015) 13–35, https://doi.org/10.1016/j.marpolbul.2015.05.062.

[67] I. Martins, J. Goulart, E. Martins, R. Morales-Roman, S. Marin, V. Riou, A. Colaco, R. Bettencourt, Physiological impacts of acute Cu exposure on deep-sea vent mussel *Bathymodiolus azoricus* under a deep-sea mining activity scenario, Aquat. Toxicol. 193 (2017) 40–49, https://doi.org/10.1016/j.aquatox.2017.10.004.

[68] R. Company, H. FelÌcia, A. Serafim, A.J. Almeida, M. Biscoito, M.J. Bebianno, Metal concentrations and metallothionein-like protein levels in deep-sea fishes captured near hydrothermal vents in the Mid-Atlantic Ridge off Azores, Deep-Sea Res. I 57 (7) (2010) 893–908, https://doi.org/10.1016/j.dsr.2010.02.005.

[69] M. Cronin, I.M. Davies, A. Newton, J.M. Pirie, G. Topping, S. Swan, Trace metal concentrations in deep sea fish from the North Atlantic, Mar. Environ. Res. 45 (3) (1998) 225–238, https://doi.org/10.1016/S0141-1136(98)00024-5.

[70] C. Hauton, A. Brown, S. Thatje, N.C. Mestre, M.J. Bebianno, I. Martins, R. Bettencourt, M. Canals, A. Sanchez-Vidal, B. Shillito, J. Ravaux, M. Zbinden, S. Duperron, L. Mevenkamp, A. Vanreusel, C. Gambi, A. Dell'Anno, R. Danovaro, V. Gunn, P. Weaver, Identifying toxic impacts of metals potentially released during deep-sea mining—a synthesis of the challenges to quantifying risk, Frontiers in Marine Science 4 (368) (2017), https://doi.org/10.3389/fmars.2017.00368.

[71] S. Fuchida, A. Yokoyama, R. Fukuchi, J.-i. Ishibashi, S. Kawagucci, M. Kawachi, H. Koshikawa, Leaching of metals and metalloids from hydrothermal ore particulates and their effects on marine phytoplankton, ACS Omega 2 (7) (2017) 3175–3182, https://doi.org/10.1021/acsomega.7b00081.

[72] S.E. Hook, N.S. Fisher, Reproductive toxicity of metals in calanoid copepods, Mar. Biol. 138 (6) (2001) 1131–1140, https://doi.org/10.1007/s002270000533.

[73] L.D. Bilenker, G.Y. Romano, M.A. McKibben, Kinetics of sulfide mineral oxidation in seawater: implications for acid generation during in situ mining of seafloor hydrothermal vent deposits, Appl. Geochem. 75 (2016) 20–31, https://doi.org/10.1016/j.apgeochem.2016.10.010.

[74] S.A.L. Paul, B. Gaye, M. Haeckel, S. Kasten, A. Koschinsky, Biogeochemical regeneration of a nodule mining disturbance site: trace metals, DOC and amino acids in deep-sea sediments and pore waters, Frontiers in Marine Science 5 (2018), https://doi.org/10.3389/fmars.2018.00117.

[75] D.O. Jones, S. Kaiser, A.K. Sweetman, C.R. Smith, L. Menot, A. Vink, D. Trueblood, J. Greinert, D.S. Billett, P.M. Arbizu, T. Radziejewska, R. Singh, B. Ingole, T. Stratmann, E. Simon-Lledo, J.M. Durden, M.R. Clark, Biological responses to disturbance from simulated deep-sea polymetallic nodule mining, PLoS One 12 (2) (2017), https://doi.org/10.1371/journal.pone.0171750 e0171750.

[76] L. Marsh, V.A.I. Huvenne, D.O.B. Jones, Geomorphological evidence of large vertebrates interacting with the seafloor at abyssal depths in a region designated for deep-sea mining, Royal Society Open Science 5 (8) (2018) 180286, https://doi.org/10.1098/rsos.180286.

[77] R. Huys, D. Thistle, *Bathycamptus eckmani* gen. et spec. nov. (Copepoda,

Harpacticoida) with a review of the taxonomic status of certain other deepwater harpacticoids, Hydrobiologia 185 (1989) 101–126, https://doi.org/10.1007/BF00010809.

[78] L.A. Levin, A.R. Baco, D. Bowden, A. Colaço, E. Cordes, M.R. Cunha, A. Demopoulos, J. Gobin, B. Grupe, J. Le, A. Metaxas, A. Netburn, G.W. Rouse, A.R. Thurber, V. Tunnicliffe, C. Van Dover, A. Vanreusel, L. Watling, Hydrothermal vents and methane seeps: rethinking the sphere of influence, Frontiers in Marine Science 3 (2016), https://doi.org/10.3389/fmars.2016.00072.

[79] R.E. Boschen, A.A. Rowden, M.R. Clark, J.P.A. Gardner, Mining of deep-sea seafloor massive sulfides: a review of the deposits, their benthic communities, impacts from mining, regulatory frameworks and management strategies, Ocean Coast Manag. 84 (2013) 54–67, https://doi.org/10.1016/j.ocecoaman.2013.07.005.

[80] C. Du Preez, C.R. Fisher, Long-term stability of back-arc basin hydrothermal vents, Frontiers in Marine Science 5 (2018), https://doi.org/10.3389/fmars.2018.00054.

[81] C.R. McClain, S.M. Hardy, The dynamics of biogeographic ranges in the deep sea, Proceedings of The Royal Society B 277 (2010) 3533–3546, https://doi.org/10.1098/rspb.2010.1057.

[82] A. Vanreusel, A. Hilario, P.A. Ribeiro, L. Menot, P.M. Arbizu, Threatened by mining, polymetallic nodules are required to preserve abyssal epifauna, Sci. Rep. 6 (2016) 26808, https://doi.org/10.1038/srep26808.

[83] A. Boetius, M. Haeckel, Mind the seafloor, Science 359 (6371) (2018) 34.

[84] ISA, Consolidated Regulations and Recommendations on Prospecting and Exploration, Revised Edition, The International Seabed Authority, Kingston, Jamaica, 2015, p. 262.

[85] ISA, Design of IRZs and PRZs in Deep-Sea Mining Contract Areas, International Seabed Authority, Kingston, Jamaica, 2018, pp. 1–8 Briefing Paper 02/2018.

[86] M.R. Clark, M. Consalvey, A.A. Rowden, Biological Sampling in the Deep Sea, John Wiley & Sons, Ltd., 2016, p. 472.