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Highlights

- There is growing likelihood of minerals mining in the deep sea. (64)
- Assessing the significance of resulting environmental impacts takes on urgency. (79)
- The ISA is developing regulations for seabed mining which must prevent serious harm.
- Defining “serious harm” is critical to effective regulation of mining activities. (82)
- Deep faunal vulnerabilities derive from low growth rates, species longevity and rarity.
- Connectivity, resilience, and cumulative impacts are key to significance assessment.

ABSTRACT

Increasing interest in deep-seabed mining has raised many questions surrounding its potential environmental impacts and how to assess the impacts’ significance. Under the United Nations Convention on the Law of the Sea (UNCLOS), the International Seabed Authority (ISA) is charged with ensuring effective protection of the marine environment as part of its responsibilities for managing mining in seabed areas beyond national jurisdiction (the Area) on behalf of humankind. This paper examines the international legal context for protection of the marine environment and defining the significant adverse change that can cause “serious harm”, a term used in the ISA Mining Code to indicate a level of harm that strong actions must be taken to avoid. It examines the thresholds and indicators that can reflect significant adverse change and considers the specific vulnerability of the four ecosystems associated with the minerals targeted for mining: (1) manganese (polymetallic) nodules, (2) seafloor massive (polymetallic) sulphides, (3) cobalt-rich (polymetallic) crusts and (4) phosphorites. The distributions and ecological setting, probable mining approaches and the potential environmental impacts of mining are examined for abyssal polymetallic nodule provinces, hydrothermal vents, seamounts and phosphorite-rich continental margins. Discussion focuses on the special features of the marine environment that affect the significance of the predicted environmental impacts and suggests actions that will advance understanding of these impacts.

Key Words: serious harm; deep-sea mining; seafloor massive sulphides; manganese nodules; cobalt-rich crusts; phosphorites

1. Introduction

Interest is accelerating in exploring the deep ocean with the intent to exploit seabed minerals [1]. Minerals of interest include manganese nodules found on the abyssal plains [2], seafloor massive sulphides (SMS) found at active and inactive hydrothermal vents [3], cobalt-rich crusts on seamounts [4], and phosphorites found along continental margins [5]. Although commercial mining for deep-seabed minerals has yet to take place, all of these resources are under exploration in areas within and beyond national jurisdiction. Licenses to mine have been awarded for SMS exploitation by the government of Papua New Guinea, for metal-rich sediments in the Red Sea jointly by the Governments of Saudi Arabia and Sudan [6], and for offshore phosphorites (with environmental clearance pending) by the government of Namibia. Other companies and government agencies are submitting permit applications for exploitation within some national jurisdictions [7,8]. As the new industry of deep- seabed mining commences, regulatory bodies are faced with difficult permitting decisions, requiring balancing potential economic gains with impacts on other ocean users, local community and civil society concerns and international and national legal obligations to ensure effective protection of the marine environment from harmful effects that may arise from seabed mining activities [9].

Environmental protection regulations to be enacted and implemented by the ISA in the future, including functional distinctions and definitions of "harmful effects" and "serious harm," will have far-reaching consequences both beyond and within national jurisdictions. Under UNCLOS, where mining activities may cause serious harm, the ISA has the power to: (i) set-aside areas where mining will not be permitted, (ii) deny a new application for a contract to conduct seabed mineral activities; (iii) suspend, alter or even terminate operations, and iv) hold the contractor and its sponsoring state liable for any environmental harm if it ensues (UNCLOS Art. 162((2) (w) and (x) and 165 (2)(k) and (l) and Annex III Article 18). Such standards will also inform national laws and regulations for mining activities within national jurisdiction, for such rules are to be "no less effective than" international rules, standards, recommended practices and procedures (UNCLOS Art. 208).

Of particular importance when designing a system to evaluate the significance of harm in the deep sea, where "serious harm" is used as the key trigger for preventive and precautionary action, are answers to the following questions:

1. How is "serious harm" defined in the context of deep-seabed mining?
2. What are the key factors or parameters to measure to inform the decision about whether an impact constitutes serious harm or not?
3. What are the special features of the deep-sea habitats targeted by mining companies that affect the significance of impacts?

In this paper, which is based on a workshop held in 2014, these questions are addressed by first examining current definitions that may inform our understanding of "serious harm" and the legal requirements to avoid such harm. Ecological and ecosystem parameters are considered that may be measured and there is a discussion of environmental thresholds and triggers for action when serious harm is predicted or is otherwise likely to occur. The mineral resources are then introduced, including distributions and ecological setting, the mining approach as understood at present, potential environmental impacts of mining, the distinctive environmental and ecological features of the associated ecosystem that inform the significance of impacts, and recommended actions to advance understanding of impacts. The need to consider cumulative impacts is presented, before finally concluding with the overall implications of the issues that surround assessing the significance of harm for decision-makers and regulators with respect to deep-seabed mining activities. A key challenge will be to formulate regulations that prevent "serious harm" as well as ensure overall effective protection of the marine environment. Table 1 consolidates much of this information.

2. The international legal context for defining "Serious Harm"

The United Nations Convention on the Law of the Sea (UNCLOS) is the legal framework guiding international management of deep-seabed mining in the Area beyond national boundaries (the Area). In the interests of ensuring equitable, rational and sustainable development of seabed mineral resources, UNCLOS designates the seabed Area and its resources as the "common heritage of mankind" (UNCLOS, Part XI, Art. 136). (The term "resources" is defined in the context of UNCLOS Part XI on the Area as "all solid, liquid or gaseous mineral resources *in situ* in the Area at or beneath the seabed, including polymetallic nodules"). All rights to the resources of the Area are vested in mankind as a whole, on whose behalf the International Seabed Authority (ISA) is to act ((UNCLOS Art. 137.2). Activities in the Area are to be carried out for the benefit of mankind as a whole, taking into particular consideration the interests and needs of developing States (UNCLOS Art. 140). Developing States are to benefit through not only a share in the financial and other economic benefits derived from mining activities in the Area, but also through provisions designed to promote capacity building, technology transfer, and access to and participation in marine scientific research and mining-related activities in the Area (UNCLOS Art. 140, 143, 144, 148) including training programs conducted by the contractors (UNCLOS Annex III Article 15).[10]

An equally important objective as well as legal obligation under UNCLOS for both States and the ISA is to ensure "effective protection" of the marine environment from "harmful effects" which may arise from seabed mining activities (Article 145). For this purpose the ISA is required to adopt "appropriate rules, regulations and procedures for *inter alia*, (a) the prevention, reduction and control of pollution and other hazards to the marine environment, including the coastline, and o*f interference with the ecological balance of the marine environme*nt **…** and (b) the protection and conservation of the natural resources of the Area and the prevention of damage to the flora and fauna of the marine environment" (UNCLOS Art. 145 (a) and (b))[11]. This is in addition to other obligations in UNCLOS that call for, inter alia, the protection and preservation of the marine environment," and the taking of measures "necessary to protect and preserve rare or fragile ecosystems as well as the habitats of depleted, threatened or endangered species and other forms of marine life (UNCLOS Art. 192, 194(5)).

Existing ISA regulations for seabed mineral exploration of manganese nodules, SMS and cobalt-rich crusts provide only a definition for "serious harm". Under these regulations, "serious harm to the marine environment" is defined to mean "any effect from activities in the Area on the marine environment which represents a **significant adverse change** in the marine environment determined according to the rules, regulations and procedures adopted by the Authority on the basis of internationally recognized standards and practices" (ISA Regulations (nodules), [12]; ISA Regulations (sulphides); [13], ISA Regulations (crusts), [14]). Such standards, as spelled out in the regulations and an Advisory Opinion by the International Tribunal for the Law of the Sea, are to ensure the application of "best environmental practices and the precautionary approach" ([13] Regulations 31(2); [15]).

The potential for serious harm entails serious consequences. As required by UNCLOS Art. 165(2)(l), the Legal and Technical Commission (LTC), the ISA's advisory body, is to, among other tasks, develop recommendations to the Council, the ISA's executive body, to disapprove mining in areas where "substantial evidence indicates the risk of serious harm to the marine environment". The LTC is also empowered to develop recommendations for emergency orders during mining operations to "prevent serious harm to the marine environment" (UNCLOS Art. 165 (k)). In turn, the ISA Council is required to issue emergency orders, which may include orders for the suspension or adjustment of operations, to prevent serious harm to the marine environment arising out of activities in the Area (UNCLOS, Art. 162(2)(w)).

Unless mining proponents and permitting decision-makers have clear and comprehensive parameters for what constitutes both "effective protection" as well as "serious harm" and associated significant adverse change to the marine environment, there will be a risk that seabed mining could cause unacceptable impacts.

Some helpful guidance for defining serious harm may be drawn from the definition of "significant adverse impact" in the International Guidelines adopted in the context of deep-sea bottom fishing on the high seas by the FAO Food and Agriculture Organization in 2009. These guidelines were developed to help states and regional fisheries management organizations (RFMOs) implement a United Nations General Assembly Resolution of 2006 which called upon them to, among other things, "assess, on the basis of the best available scientific information, whether individual bottom fishing activities would have significant adverse impacts on vulnerable marine ecosystems and to ensure that, if it is assessed that these activities would have significant adverse impacts, they are managed to prevent such impacts, or not authorized to proceed" (UNGA Resolution 61/105 para 83(a)).

This FAO definition is particularly relevant as the ISA Mining Code contains a similar formulation with respect to exploration impacts, which provide that:

> *"The Commission shall develop and implement procedures for determining, on the basis of the best available scientific and technical information….,whether proposed exploration activities in the Area would have serious harmful effects on vulnerable marine ecosystems [, including seamounts and hydrothermal vents], and ensure that, if it is determined that certain proposed exploration activities would have serious harmful effects on vulnerable marine ecosystems, those activities are managed to prevent such effects or not authorized to* proceed." (ISA Regulations (nodules 31.4; sulphides 33.4; crusts 33.4)

The FAO Guidelines provide that significant adverse impacts are "those that compromise ecosystem integrity" (FAO, 2009, para 17). It lists six factors to consider: (1) intensity and severity of the impact; (2) spatial extent of the impact relative to habitat availability; (3) sensitivity and vulnerability of the ecosystem to the impact; (4) ability for the ecosystem to recover; (5) the extent of ecosystem alteration; and (6) the timing and duration of the impact relative to species and habitat needs ([16] para 18). It further considers duration and frequency of impacts as metrics for determining significance ([16], para 19-20). In addition the authors recommend including the concepts of: (7) probability of impacts occurring; (8) cumulative effects of impacts, and (9) scientific uncertainty related to impacts, when determining what deep-seabed mining impacts should be considered "significant" The FAO Guidelines also provide criteria for identifying "vulnerable marine ecosystems" in the context of deep-seabed bottom fishing, but their applicability to seabed mining is beyond the scope of this paper.

In reality, assessing any changes to deep-sea ecosystems induced by mining activities is challenging at best. The remoteness and expense of studying these ecosystems has resulted in major knowledge gaps concerning habitat distribution (regionally and globally), ecosystem structure and function. These gaps include species identities (most deep-sea species are undescribed), biodiversity, distribution patterns and biogeography, community distributions, dynamics, trophic relationships, population connectivity, physiological tolerances, ecosystem tolerances, and resilience.. Without this baseline information, it is difficult to assess the impacts of a human activity in space and time, to determine whether these impacts are enduring or transitory. The use of a systematic approach based on a robust ecological assessment of the key physical, biogeographic, ecological, and biodiversity features of the deep seafloor will be useful when dealing with the challenges of managing a large underexplored area [17]. Cumulative impacts of multiple mining actions (in space and time) and additive perturbations from direct human activities (e.g., fishing activities, contaminants and spills), and climate-change related stressors (e.g., warming, ocean acidification and deoxygenation) must also be considered when evaluating the significance of changes to and/or impacts on deep-sea ecosystems [18,19].

3. Significant adverse change: Thresholds and triggers

An ecological threshold is a point at which changes in an important ecosystem property or phenomenon have exceeded normal ranges of variability [20]. Such thresholds may, but will not necessarily be, "tipping points" at which a small further change will abruptly produce a large ecosystem response [20] resulting in a regime shift (change in state). In the context of deep-seabed mining, ecological thresholds should help to inform the determination of when an adverse change and/or impact may be considered a significant one, i.e. 'serious harm'. The identification of ecological thresholds requires, at the very least, knowledge of long-term (years to decades) average baseline conditions and natural ecological variability. Although natural variability is often determined from time series investigations of 3-25 years, the appropriate time period for assessment will be system-dependent [21]. With an understanding of ecological thresholds, decision-makers can determine: (1) what impacts are expected to exceed ecological thresholds and therefore should not be permitted; and (2) what impacts could exceed ecological thresholds and therefore require management, monitoring and then cessation of operations if the threshold is neared.

However, one of the greatest challenges for environmental management of the deep sea is the substantial lack of data, making the use of ecological thresholds for decision-making in deep-seabed mining a difficult one at best. The mandate to apply a precautionary approach and a lack of baseline data necessary to define ecological thresholds should lead to heightened restrictions, including at least slow ramping up of activities until thresholds are better characterized [1]. Key metrics that may serve as threshold indicators are measures of biodiversity, abundance, habitat quality, population connectivity, heterogeneity levels, and community productivity.

If information is not available to set particular ecological thresholds, a suite of other indicators can be used to determine the likelihood of significant adverse change and impacts, including those that address species-, community- or ecosystem-level impacts. Here all three ecological levels are considered. Significant species-level changes or impacts include: (i) extinction; (ii) significant decline in abundance; (iii) decline in foundation species; (iv) reduction below critical reproductive density; (v) loss of source populations; and/or (vi) loss of critical stepping-stone populations. Community-level impacts include (i) alteration of key trophic linkages among species in a community; (ii) reduction in species diversity beyond natural levels of variability; and/or (iii) regional declines in habitat heterogeneity, such as loss of entire habitats or community types. At the ecosystem-level, impairment of important ecosystem functions such as biomass production, nutrient recycling or carbon burial can lead to loss of major ecosystem services upon which society depends. They may include loss of carbon sequestration capacity, genetic resources, or fisheries production. These impacts can be evaluated in local, regional or global contexts. While the concept of ecosystem services underlies many of the above indicators and metrics, threshold levels of decline in services have yet to be identified. These services are likely to vary by habitat, and the spatial and temporal scale at which changes are significant to the ecosystem have not been defined here. Additional measures that reflect key services are needed and a quantifiable measure of lost services will need to be incorporated into significance assessment [22].

4. Deep-seabed mining resources and potential impacts

4.1 *Deep-seabed mining activities to date*

As of 2016 there are 25 exploration contracts approved by the ISA: four for cobalt-rich crusts, each 3,000 km^2 in the South Atlantic and Mid-Pacific; 16 for manganese nodules, each up to 75,000 km^2 in the Clarion Clipperton Fracture Zone in the Pacific (15) and in the Indian Ocean (1); and five for SMS, each approximately 10,000 km^2 in the Indian Ocean and on the Mid-Atlantic Ridge (Figure 1). There also has been commercial interest in deep-seabed minerals within national jurisdictions, including in the Pacific Islands region, Mexico, Namibia, New Zealand, Saudi Arabia, South Africa, and Sudan. For example, many deep-seabed mineral licenses for *exploration*– evaluating resources prior to the production phase of mining – have been issued over recent years for SMS by Fiji[2], Papua New Guinea[3], Solomon Islands[4] and Tonga.[5] In August 2015, the Cook Islands invited bids for deep-seabed mineral exploration of manganese nodules within its waters but none have been received.[6] The world's first deep-seabed mining project may commence as early as 2019 in Papua New Guinea's waters, although financial difficulties are causing delays.[7] The mining company, Nautilus Minerals Inc., was granted a mining lease in 2011 by Papua New Guinea Government in the South Pacific Bismarck Sea containing SMS deposits.[8] In 2010, Saudi Arabia and Sudan granted a production license for a SMS project known as 'Atlantis II' in the Red Sea, managed by a Saudi Arabian/Canadian consortium. However, there have been no public indications of imminent intention to commence production in this site.[9] The Namibian government has granted two mining licenses (to Lev Leviev and to Namibian Marine Phosphate), but a moratorium was instituted while further environmental impact assessment was conducted. As of August 2016 the official decision regarding marine phosphate mining in Namibian waters had not been announced, with the matter of strategically assessing the cumulative environmental impacts under review by the Government of Namibia.[10] As of Sept. 2016, a decision on phosphate mining in Namibian waters is still pending. Exploration and mining claims for phosphorites have been made in South Africa, New Zealand and Mexico, although the environmental ministries of the latter two States have recently rejected these based on environmental concerns[11][12]. It is important to note that no exploitation of deep-seabed minerals has taken place yet. This situation presents an unusual opportunity for the architects of relevant legal regimes, and the permitting decision-makers, to make informed decisions at the outset.

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[2] http://www.lands.gov.fj/images/tenementmaps/june15/DeepSeaExpl_June2015.pdf
[3] http://portal.mra.gov.pg/Map/ (search on 'Nautilus' and 'Bismarck')
[4] Page 14, SPC-SOPAC Division Published Report 151 – Lily, Tawake, Ishmael, 2012: http://www.sopac.org/dsm/public/files/reports/country/PR151_Solomon%20national%20workshop_hl-at.pdf
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[7] http://subseaworldnews.com/2016/06/29/nautilus-looks-to-save-its-deep-sea-mining-project/
[8] http://www.nautilusminerals.com/s/Projects-Solwara.asp and news release of 16 June 2015, available here: http://www.nautilusminerals.com/s/Media-NewsReleases.asp?ReportID=712314
[9] http://www.diamondfields.com/s/AtlantisII.asp
[10] B. Currie, pers. communication
[11] DECISION ON MARINE CONSENT APPLICATION Chatham Rock Phosphate Limited To mine phosphorite nodules on the Chatham Rise http://www.epa.govt.nz/eez/EEZ000006/EEZ000006_CRP%20Final%20Version%20of%20Decision.pdf
[12] https://www.earthworksaction.org/earthblog/detail/victory_mexico_seabed_mining_project_scrapped#.V93SIo7OrDI

Below four of the resources currently being considered for deep-seabed mining in national or international waters are addressed. Hydrothermal, sulfidic sediments (under license in the Red Sea) were not discussed at our workshop and thus are not treated here. The text below distinguishes effective protection of the marine environment from harmful effects, which is the general overarching objective, from "serious harm" that causes significant adverse impacts, and under UNCLOS as well as current regulations, should prevent mining from occurring in a specific area or require suspension or adjustment of mining activities to prevent serious harm.

4.2 Manganese nodules

4.2.1 Mineral resource: Manganese nodules (also called polymetallic nodules) are mineral precipitates of manganese, iron oxides and other metals. Nodules range in size from millimeters up to a half meter or more. The nodules of greatest commercial interest contain relatively high levels of nickel and copper (e.g., 1.5% of the nodule weight), cobalt, zinc, and traces of other metals (e.g., molybdenum, lithium) important to high-tech industries [23]. The nodules form extremely slowly (with estimated growth rates of 2-15 mm per million years) and occur over extensive areas in the abyssal Pacific, Indian and Atlantic Oceans, where they provide hard-substrate habitat for a variety of fauna (e.g., sponges, foraminifera). The nodules currently of greatest commercial interest occur beneath the relatively low productivity environment at 10-20 degrees north of the equator in the Pacific Ocean in the Clarion Clipperton Zone (CCZ), within an area of ~6 million km^2, with nodule abundances ranging from <1 to >35 kg m^{-2} [23].

4.2.2 Mining overview: The extraction of manganese nodules is envisioned to be carried out by a series of remotely operated, technologically advanced nodule harvesters that are likely to plough, scrape, and/or vacuum the seafloor over large areas (300-800 km^2 of seabed per mining operation per year, [24]. As envisioned by some companies (e.g., UK Seabed Minerals), crushed or whole nodules and entrained sediments will be pulled up a riser pipe to the surface, where nodules will be offloaded to a production support vessel for transport to land. Sediment-containing water will most likely be returned to the ocean at the site at an, as yet, undetermined depth.

4.2.3 Impacts from mining on habitat/resources: Manganese nodule-mining operations could have major impacts over large abyssal regions. Removal of nodules will remove specialized fauna (e.g., foraminifera and sponges) that live on the nodules [25,26,27], together with organisms that live in the soft sediment patches between and under the nodules [24,28]. Epifaunal densities increase with nodule density, and alcyonacean and antipatharian corals are present in the CCZ only where nodules occur [29]. In addition, there appears to be a high diversity of nodule-obligate megafauna in the CCZ [30]. Nodule removal, sediment disturbance and plume perturbations have the potential to reduce habitat complexity, biodiversity and ecosystem function over large spatial scales both at the seafloor and in the water column. Some effects will likely persist for millennia because the formation of new nodules, and the habitats and heterogeneity they provide, is estimated to take millions of years [29].

The nodule extracting equipment will remove and disturb the top 15-40 cm of sediment that provides food for a high diversity of surface deposit-feeding organisms. The extracting equipment will likely also compress seafloor sediments beyond normal conditions, adversely affecting biota living within the sediments, benthic colonization and other processes (e.g., seafloor biogeochemistry; [31]. Nodule collection will cause sediment plumes during discharges that may disperse at least 10s and possibly hundreds of kilometers [24,27]. Such plumes have the potential to bury or smother seafloor organisms and habitats, and prevent larval settlement and colonisation, because background rates of sediment deposition are extremely low (e.g., [32,33]. Studies have shown negative effects from 1 cm of sediment deposition in the CCZ [34], and the most food-poor area of the CCZ (NW regions in the CCZ) will most likely be more sensitive to sedimentation. Plumes dispersing through the water column may clog the filtering membranes of suspension-feeding fauna (both benthic and pelagic). Resuspended sediments may also release oxygen-depleted pore waters and chemicals (e.g., heavy metals from the sediment) with potential biogeochemical or ecotoxicological effects [35], and could affect vision, feeding and communication processes (e.g., bioluminescence) in the pelagic environment. The chronic effects of recurrent sediment plumes within an abyssal mining region remain unstudied but could be deleterious in regions such as the abyssal CCZ where natural sediment resuspension has not been documented and appears very unlikely based on observations and measurements [36].

Waste materials from initial at-sea separation are expected to be released through a discharge pipe into the middle of the water column or at the water/seafloor interface, but the resulting sediment plumes may also cause impacts on midwater and mesopelagic species in the water column. Suspended particle effects on feeding, prey avoidance, and other ecological processes are likely but unstudied. In addition, biota throughout the water column might be affected by sediment leakage from the system used to lift the nodules to the surface, and sediment runoff from the mining support vessel could have local impacts on photosynthetic productivity in surface waters.

In addition to physical impacts caused by mining, sound from mining machines, pumps, platforms and vessels may occur at the sediment-water interface, mid-depth water column and surface water column. Anthropogenic sound is known to cause harmful effects to marine mammals [37], but impacts on lower trophic level organisms are poorly understood, even in shallow-water environments. In addition to sound, light from mining operations may blind, attract, or misdirect organisms, altering their visual capabilities, communications, mate finding or prey avoidance capacity [38].

4.2.4 Special features that affect significance of predicted impacts: Several traits characterize abyssal habitats where nodules are found that are key to understanding the significance of predicted impacts and recovery potential of affected ecosystems, and thus the potential for mining to inflict 'serious harm'.

(1) Manganese nodules are found underlying mesotrophic/oligotrophic water masses and the fauna inhabiting the water column and seafloor in these regions generally exist under extremely stable physical conditions (including low sedimentation rates, low current velocities and few/no resuspension events over decade to century time scale). ***Therefore, extensive resuspension and deposition of sediments over large spatial scales will cause a substantial change to the existing ecosystem, with harmful effects. Some of these changes may be sufficiently widespread to constitute serious harm to vulnerable marine ecosystems and/or to the wider marine environment.***

(2) Abyssal ecosystems in the CCZ are very food poor, with biomass, community structure, production, growth rates, and recolonization rates all controlled by the very low flux of particulate organic material sinking from the distant euphotic zone [39]. ***Therefore, ecosystem recovery rates from mining disturbance will be very slow, so impacts on the sediment-dwelling biota from single mining activities may persist for decades to centuries, causing harmful effects.***

(3) Manganese nodules provide much of the available hard substrate in the deep waters of the CCZ and other abyssal plains regions, and nodules can take millions of years to form [40]. ***Nodule removal will eliminate much of this habitat, as well as the specialized nodule fauna*** [29]. Surveys conducted in the CCZ along tracks from trawling or experimental mining simulations up to 37 years old suggest that epifauna is almost completely absent and recovery of the ecosystem in this area is slow [29]. ***Complete removal of nodules will cause significant adverse change for long periods of time (millennia), possibly over areas hundreds of km in extent.***

(4) Many of the fauna inhabiting soft sediments found amongst the nodules inhabit the top 5-10 cm of sediment [28], and their recovery from sediment disturbance is likely to take a long time, i.e., decades to centuries (e.g.,[41]. ***Removal of sediment during nodule extraction will damage or kill the soft-sediment fauna over large spatial scales, reducing biodiversity and causing harmful effects within a mining claim. Timescales for recovery are poorly constrained, but small-scale disturbance tests suggest that recovery may take decades to centuries***.

(*5*) Much of the fauna inhabiting the abyssal regions where nodules occur has not been described or sampled. In those areas that have been sampled, levels of biodiversity appear to be high. Species and dispersal ranges are also poorly known, and the relationships between community structure and ecosystem function are uncertain. ***It is possible that the mining of manganese nodules could cause serious harm through the extinction of hundreds or more of undescribed species, especially those with small biogeographic distributions, thereby altering evolutionary potential, biodiversity (of species and genes), and ecosystem processes in the abyss. Such changes may be sufficient to be considered serious harm.***

4.2.5 Actions toward understanding significant impacts of manganese nodule extraction.

- More extensive studies of pelagic and benthic biodiversity, species distributions and dispersal ranges, and ecosystem resilience, functions and services are needed in areas targeted for manganese nodule extraction to better characterize baseline conditions and assess potential significant mining impacts. Communication among scientific researchers working in the same region (e.g., on nearby claims) will be important.
- Realistic, large-scale mining disturbance studies may be needed to assess the spatial scales and intensities of disturbance resulting from mining (including cumulative impacts).
- Determining the time scales of recovery of affected soft-sediment and nodule communities and pelagic ecosystems is also required, but the very long recovery times expected (up to millennia) will make estimation of recovery times challenging.

4.3 Seafloor massive sulphides

4.3.1 Mineral resource: Seafloor massive sulphides (SMS; also called polymetallic sulphides) are deposits found associated with active hydrothermal vents and inactive sulphide deposits in a variety of geological settings, including mid-ocean ridges, back-arc basins, volcanic arcs and intraplate volcanoes, at hundreds of highly localized vent sites, often at depths of 1200-3000 m [40,42,43]. Active vents are defined here as systems with evident hydrothermal fluid flux (i.e., temperature and/or chemical anomalies) supporting chemoautotrophic ecosystems typically dominated by invertebrate-microbial symbioses. Inactive sulphide deposits lack surficial evidence of hydrothermal fluid flux and lack dense populations of symbiont-hosting invertebrate taxa. Instead, they are often visually depleted in biota, with only an occasional megafunal invertebrate observed. Because of this general perception of inactive sulphide deposits as biologically depauperate, they have not attracted much exploration or biological characterization. However, the Gorda Ridge (Escanaba Trough) sulphide mounds are one example of inactive deposits that host a large megafaunal population of brachiopods [44], sponges, corals and barnacles are reported in Manus Basin [45], and corals and echinoids are found in high density at inactive sites on the Kermadec volcanic arc [46].

Sulphide deposits generated by seabed hydrothermal systems contain high-grade ore that includes minerals such as copper sulphide (chalcopyrite) and zinc sulphide (sphalerite), gold and silver [7]. The geochemistry of the host rock and fluid compositions in the different geological settings shape both the ore concentrations in the deposits and the composition and functioning of the ecosystem. At present, there are approximately 400 known active vent fields, with estimates of 1300 total on mid-ocean ridges and back-arc spreading centers [42,47,48]. Where these vent systems occur on intermediate- or slow-/ultra-slow spreading centers, they are expected to have accumulated fossil massive sulphide deposits that may have commercial potential.

The distinction between active hydrothermal vents and inactive sulphide deposits is important in considering environmental management needs; the two types of ecosystems associated with these deposits support different communities and have different vulnerabilities to consider [49,50]. However, prospective mine sites often contain both active and inactive deposits, and so the vulnerability of communities at both will need to be assessed.

4.3.2 Mining overview: Existing concepts for SMS mining envision the use of multiple remotely operated, large, technologically advanced machines to undertake open-pit mining once the sediment overburden is removed [51]. The machines will cut, crush, and gather the ore and then send it as slurry to the production support vessel via an enclosed riser and lifting system. Once on board the mining support vessel, the slurry will be dewatered to collect all but the finest particles (to ~10 um), then seawater and fine particles will be discharged back into the sea at a depth close to the seabed. The ore will be transported to land for further processing. While single mining sites may cover local areas as small as 100 m^2; multiple sites in close proximity are likely to be mined, thus introducing cumulative harm within the exploited region that should be considered in assessing significant adverse impact.

4.3.3 Impacts from mining on habitat/resources

4.3.3.1 Active vents. SMS mining operations will have a direct impact on the mining site, removing the substratum and its associated fauna and thus reducing diversity at all levels: genetic, species, functional, and habitat [38,43,52] and causing serious harm. The 3-dimensional structure of the habitat will be flattened, reducing habitat heterogeneity to a minimum and changing the substratum characteristics (e.g., porosity, particle size distribution, mineralogy), as well as the geochemical and hydrodynamic regimes [38,50]. High turbidity plumes with elevated metal concentrations generated by the mining activity and from the return into the sea of the water that has been separated from the ore material on-vessel [53] could affect pelagic and benthic populations downstream, potentially impeding vision, reducing bioluminescence, clogging organs of filter- and particle-feeders, disrupting larval development and settlement and potentially resulting in toxic effects from bioaccumulation of metals [27,43]. As with manganese nodule mining, light and noise from seabed activities may cause additional impacts. At active sites, these physico-chemical impacts will likely be temporary, since venting is expected to persist and new chimneys will precipitate and coalesce [54]. Local fauna will be crushed by the mining operations (sessile and slow moving fauna) or dispersed to other areas (mobile fauna such as fish and some large crustaceans), thus reducing biodiversity and abundance totally or to very low levels, in the absence of mitigation. This direct impact is particularly of concern for vent-endemic and rare species. At fast- and intermediate-spreading ridges, active vent communities are known to recover from catastrophic impacts (volcanic eruptions) on a decadal time scale [38]. The rate of recovery following a catastrophic disturbance at active vents on slow- or ultra-slow spreading ridges or in back-arc basins is unknown.

4.3.3.2 Inactive vents. A single mining event at an inactive vent will eliminate local fauna and cause harm, but the extent to which this fauna is endemic is unknown. If the fauna of inactive vents is also found on hard substrata throughout a ridge system, the severity of the impact is considerably lessened in terms of lost biodiversity. However, where populations of particular taxa are relatively large at inactive vent sites, these populations could be disproportionately important for the maintenance of populations elsewhere through the supply of larval recruits. Recovery of inactive vents from mining activities is not known –in fact the fauna of inactive vents is hardly known [45, 49]– but is presumed to be slow, on the order of decades to centuries [38, 46]. To assess the potential for such recovery of populations and communities, a sound understanding of regional species distributions, their genetic diversity, reproductive ecology, and dispersal potential, as well as regional hydrodynamic regime that will drive dispersal of larvae, resulting gene flow and colonisation, is necessary. This must be placed within the context of temporal dynamics, natural variation, and succession of indicator species [52].

At inactive sites, mining will remove the vertical topography, and modify seafloor texture and habitat heterogeneity; this will likely be a permanent effect at inactive sites, barring reactivation of fluid flow. If an inactive vent becomes active [55], once the ore is removed, the local physiography, biodiversity, and connectivity would be changed and could be enhanced.

4.3.4 Special features that affect the significance of predicted impacts at vents:

4.3.4.1 Active vents. Because active vents are naturally dynamic (including becoming inactive and subject to destructive volcanic eruptions), the fauna exhibit fast growth rates and high reproductive output, that may make them resilient to major disturbances. However, other attributes may make them particularly susceptible to cumulative impacts of multiple mining events in a region and have led to their listing as indicators of Vulnerable Marine Ecosystems [16]. Several characteristics distinguish active hydrothermal vents from most other habitats in the marine biome [56, 57, 58] and are key to understanding the significance of predicted impacts and recovery potential of affected ecosystems, and thus the potential for mining to inflict a significant adverse impact and 'serious harm':

(1) Active hydrothermal vents are spatially very limited (on the order of 100 to 500 m maximum dimension) and distributed linearly along mid-ocean ridges or patchily in seamount provinces. The population of a species at a given vent is part of a larger metapopulation. **The island-like distribution of vent habitats means that a given metapopulation may be susceptible to cumulative mining impacts (e.g., loss of reproductive populations) that interfere with connectivity among populations. A break in connectivity** (e.g., loss of populations at multiple and/or critical habitats) **would result in isolation, loss of biodiversity, and other ecological consequences, sufficient to cause significant adverse impacts and serious harm to the marine environment.**

(2) Active hydrothermal vents host taxa that are deemed likely to be adapted for and restricted to the vent environment, that is, the taxa may be endemic to vents. **Thus vent-endemic taxa have limited habitat available to them and could be at risk of a significant adverse impact and serious harm and (including extinction) if multiple and/or critical habitats are lost** beyond natural levels of habitat loss (i.e., single sites becoming inactive)**.**

(3) Geothermal activity of vents serves as a source of reduced compounds that fuel microbial chemoautotrophic primary production, which in turn supports higher trophic levels, and has an ecological influence beyond the boundaries of the active vent [59]. **Disruption of primary productivity at active vents may have a harmful effect on the secondary productivity of the surrounding seabed environment. There is no evidence to date to suggest that this would be a significant adverse impact.**

(4) Dominant host-invertebrate populations at active hydrothermal vents form biogenic habitats that support abundant smaller taxa. **Loss of biogenic habitats at an active vent may place other taxa at risk, particularly if during the recovery phase, community structure shifts to an altered state that does not include the lost biogenic habitat. This habitat loss could result in a significant change although whether the impact is adverse or positive is difficult to predict without further knowledge.**

(5) Plumes generated by mining activities will be enriched in toxic metals. **If these toxic metals become bioavailable, they could have a harmful effect on the biota (pelagic and benthic) in the plume shadow, and through bioaccumulation. The extent to which this bioavailability of toxic metals could become a significant adverse impact is not known.**

4.3.4.2 Inactive vents:

1) Inactive sulphide deposits are very poorly characterized. **Particularly if there should prove to be a rare fauna endemic to this environment, mining activities have the potential to cause a significant adverse impact, including extinction of taxa.**

2) Inactive sulphide deposits may be food poor, with biomass, community structure, production, growth rates, and recolonization rates all controlled by the very low flux of particulate organic material sinking from the distant euphotic zone [39]. ***Therefore, ecosystem recovery rates from mining disturbance will be very slow, so impacts to the sediment-dwelling biota from single mining activities may persist for decades to centuries, causing harmful effects and a significant adverse impact.***

3) Inactive vent sites of interest for mining may exist in close proximity to (or be interspersed with), active vent sites, and fauna may benefit from the higher productivity associated with the active venting. This increased food availability may support relatively large populations of filter/suspension-feeding fauna such as corals, which are often long-lived. ***Therefore, community recovery rates at inactive sites may be long (e.g., hundreds of years), and mining disturbance could also cause significant adverse change to the connectivity of those taxa that rely disproportionately on larval supply from large populations at inactive vent sites.***

4) Plumes generated by mining activities will be enriched in toxic metals. **If these toxic metals become bioavailable, could have a harmful effect on the biota (pelagic and benthic) in the plume shadow and through bioaccumulation. The extent to which bioavailability of toxic metals could become a significant adverse impact is not known.**

4.3.5 Actions toward understanding whether there will be significant adverse impacts of SMS extraction at active hydrothermal vents and inactive sulphide deposits.

- A thorough knowledge of the regional distribution of active and inactive sites and their associated fauna is necessary to understand regional variability in community composition and identify potential source and sink populations.
- Understanding connectivity of populations at active and inactive sites is critical to understanding whether mining and cumulative mining impacts in a region will result in a significant adverse effect (e.g., loss of biodiversity), in addition to serious harm. A related knowledge gap to fill is the extent to which local populations are maintained through local or long-distance recruitment events.
- Better understanding of natural community variability, succession patterns, potential alternative states for active hydrothermal vents are key ecological dynamics that would help in assessing likelihood of significant adverse effects.
- For inactive sulphide deposits, a thorough characterization of the colonizing fauna and their ecological attributes, including degree of endemicity, growth rates, fecundity, and recruitment, is critical to understand the potential for causing a significant adverse impact through mining events.
- Understanding the ecotoxicology of plumes generated by seabed mining activities on pelagic and benthic biota in the plume shadow.

4.4 Cobalt-rich crusts

4.4.1 Mineral resource: Cobalt-rich crusts (also called polymetallic crusts) form a thin mineral layer through precipitation over millions of years from the surrounding seawater, and accumulate on hardground areas of seafloor swept clear of sediments by current flow [40,60]. The thickest deposits (up to 25 cm) occur on the summits and flanks of seamounts (especially large flat-topped guyots), ridges and plateaus, fused to the basal rock. These features occur in all oceans of the world, but are most common in the Pacific Ocean, where there are estimated to be at least 50,000 seamounts and knolls [61]. The main constituents of the crusts are iron and manganese, although many other minerals occur in smaller amounts. The metals of commercial interest in cobalt-rich crusts are cobalt, nickel and manganese, and are most enriched at water depths of 800 to 2500 m [62]. The crusts also contain rare-earth elements [40, 63].

4.4.2 Mining overview: The mining of cobalt-rich crusts is more technologically complex than for manganese nodules (which occur on/in soft sediments) or SMS (which protrude from the seafloor in brittle structures) [51]. Although it will similarly require the use of large, remotely operated, technologically advanced machinery to dig into and cut, crush and gather the ore, and send it as slurry to the production support vessel through a riser and lifting system, or as whole rock material in a chain of bucket-type containers. The variable thickness of the crusts combined with the steep and rugged seamount terrain makes design and operation of the collection tools difficult. However, once on board the vessel, the processes are similar to the other mineral types. Slurry will be dewatered, the seawater and discard products will be discharged back into the sea and the ore transported to land for processing [51]. A mining-site model developed by Hein et al. [64], and endorsed by the ISA in its cobalt-rich crust regulations, involves a combination of 20 km^2 sites and a total area of about 260 km^2 over a 20-year mining life span. Subsequently, He et al. [65] suggested that to be profitable a mine site would need to cover a total area of 1,214 km^2, and be mined for 20 years to produce 1 million wet tons. This form of mining would require multiple mining sites on multiple seamounts in close proximity, and would cause cumulative impacts within the exploited region.

4.4.3 Impacts from mining on habitat and resources: Extraction of cobalt-rich crusts will cause impacts at the seafloor, through the water column, and potentially at the ocean surface [66]. The most direct and substantial effects will be on the habitats and benthic fauna at the seafloor. Here there will be substantial physical alteration of the seafloor as the crust is removed, the overall relief of the surface of the seamount will be flattened to an extent, and the amount of soft sediment will increase. Hence there is expected to be reduction in habitat heterogeneity, and changes in the geochemical characteristics of seafloor sediments. Seamounts often have high diversity and density of large, sessile animals, such as sponges and corals, as well as giant protozoans called xenophyophores, which form a biogenic habitat for other communities [67,68,69]. These organisms will be affected directly by the mining operations, and will not survive. Mobile animals, such as fish and crustaceans, may be able to disperse to other areas, but the overall biodiversity at the mining site will be reduced to very low levels. These impacts are particularly important for endemic and rare species. The capacity of affected communities to recover may be low. Typically, deep-sea invertebrate and fish species are long-lived and have slow growth rates, and their ability to recover from human disturbance (such as fishing or mining) is very low [70,71]. The potential for recovery will be affected by substrate changes, with soft sediment from mining plumes being unsuitable for many sessile species, and potentially smothering small animals and clogging the feeding structures of suspension feeders. The availability of source populations on nearby seamounts that will provide the necessary propagules (larvae, juveniles and dispersing adults) is poorly understood. Hence, both physical and biogenic habitat will be severely impacted over a long period of time (likely many decades to centuries for the fauna).

Mining for cobalt-rich crusts will generate plumes of sediment, both from the physical disturbance of the seafloor, and from any discharge of processing waste. This sediment will have direct impacts on benthic communities through smothering and burying of animals, clogging of feeding structures, preventing larval settlement and colonisation, and indirectly through metal release and accumulation through the food chain. The vigorous hydrodynamic regime on seamounts suggests that the “downstream” extent of sediment plume impacts could reach well beyond the direct site of mining, over 100s of meters [72]. Depending on the discharge depth of waste water (including fines, and small rocks), there can be impacts on plankton and fish communities throughout the water column. Effects include: potential oxygen depletion; nutrient and trace metal enrichment; changes in water clarity affecting visual predators; behavioural changes of plankton, mesopelagic fish and marine mammals from the plume density, contaminant composition, and associated noise; bioaccumulation of toxic metals in higher predators; toxic effects for early life history stages (e.g., larvae), and direct mortality of small plankton and mesopelagic fish [73].

4.4.4 Special features that affect significance of predicted impacts: Limited biological survey work has been directed specifically at cobalt-rich crust habitats, but many studies have occurred on seamounts that are known to have such crusts. From these a number of key biodiversity characteristics can be defined (after [66,74,75] that are important for understanding the significance of impact and recovery potential of seamount ecosystems.

(1) The dominant benthic fauna on seamounts are often sessile corals and sponges, which can form dense reef-like structures [76], and be much more abundant on seamounts than on continental slope habitats (e.g., [77]). The complexity and fragility of these taxa make them highly vulnerable to impact by mining operations. These corals and sponges provide important food,

habitat and refuge for a large number for associated invertebrates and fish species (e.g., [78,79,80]. ***Hence loss of the main components of many cobalt-rich crust benthic communities will have a follow-on effect to other associated species, causing serious harm through significant adverse change.***

(2) The key coral and sponge species are filter or suspension feeders, which rely upon ingesting small particulate matter from the passing seawater. High sediment/particle loading from a sediment plume can clog polyps and feeding pores, causing a reduction in respiration, or death of the animal. ***Harmful effects from mining operations will extend over the dispersal distance of the plume, i.e., over a much larger area than the direct mining site. Whether this causes serious harm will vary depending on the depths and current flow characteristics of each seamount where mining is conducted.***

(3) Many deep seamount species have high longevity, and slow growth-rates [57,68,76]. Seamount fish, which comprise major fisheries, may be one hundred or more years old, while deep-sea corals can be several thousands of years old (see review in [71]). Studies at the bathyal depths of cobalt-rich crusts have examined changes following cessation of trawl fishing and indicate that after up to 10 years there was no evidence of stony coral regrowth [70]. ***Recovery of community composition, biomass and biodiversity levels and functioning similar to the original state is likely to be very slow in part due to great longevity of organisms. Significant adverse change in long-lived seamount species will constitute serious harm, in part due to their biodiversity- and fisheries-support functions.***

(4) Recent work has demonstrated that seamounts with differing levels of cobalt-rich crusts exhibit high faunal variability [74, 75, 81], with variations in species composition and abundance between cobalt-rich crust seamounts [74]. ***The differences in species composition and abundance between seamounts means the impacts of mining will vary with location, and cannot be assumed to be the same even for adjacent mining sites.***

(5) Faunal composition changes with depth, and a potential mining depth range of 800–2500 m would impact a wide range of communities with differing species composition and abundance on a single seamount [74]. The vulnerability of communities will also change. ***The depth range covered by a mining project must be considered when evaluating whether significant adverse changes will occur.***

The food chain is supported by primary productivity based on energy from photosynthesis. The topography of a seamount can cause upwelling of nutrients and localised circulation that traps plankton [82, 83], but support of high productivity at seamounts is believed to be largely through pelagic food webs, via horizontal advection of plankton from surrounding areas (meaning pelagic energy sources are continuously renewed) and by the seamount trapping vertically migrating plankton [68,82,84]. Chemosynthetic sources of production are rare but may be associated with volcanic activity on some seamounts with cobalt-rich crusts. Hence, although direct physical impact on the seafloor will affect production of benthic invertebrates, the greater risk is any effect from near seafloor and midwater sediment plumes on the pelagic food source and production-especially the return processing waste plumes which might be higher in the water column. ***Mining activities, if the return sediment plume effects are controlled, might not alter overall seamount productivity levels to a significant extent.***

(7) Many benthic species are reported to be endemic to a seamount or group of seamounts. Whilst this is partly an artifact of sampling [85]. Stocks and Hart [86] found, overall, about 20% of seamount species had a restricted distribution. ***Mining impacts that result in the loss of certain endemic species (i.e., those with restricted geographic distributions) would represent a significant adverse change causing serious harm.***

4.4.5 Actions toward understanding significant impacts of cobalt-rich crust extraction.

- Given the depth range of cobalt-rich crust habitat, interactions with, and cumulative impacts from, commercial deep-sea fisheries and long-term ocean acidification need to be considered.
- Improved knowledge is needed of the composition, structure and function of settings where cobalt-rich crusts are common, sensitivity of benthic fauna to changes to the substrate texture (e.g., hard rock to soft sediment), and regional population connectivity (e.g., sources and sinks).
- The effects of sediment plumes generated by crust mining are poorly understood, and there is a pressing need for a greater understanding of increased sediment loads, and any associated ecotoxicity, on benthic and bentho-pelagic fauna.

4.6 Phosphorites

***4.6.1 Mineral resources**:* Phosphorites (also called phosphates) are widely distributed in the marine environment, mainly in outer shelf and upper slope unconsolidated sediments on continental margins, and particularly along boundary upwelling areas where their biogenic origin is linked to organic-rich surface sediments [86, 88]. Rich phosphorite deposits are found in the Benguela, Humboldt, California and Canary upwelling systems, off the west coast of India, and off the southern and western shelf of South Africa. Other phosphorite deposits not linked to present-day upwelling (but including regions of high productivity) are found off the east coast of North America, off Australia and New Zealand and at several island sites in the Pacific and Indian Oceans [5,85,89,90]. 0The character of the deposit varies with locality, from small granules <500 µm, to lamellae, crusts, concretions and nodules several centimeters in diameter. Deposits are concentrated at varying depths within surface sediments.

Phosphorites contain significant amounts of phosphate resulting from the concentration of the mineral apatite or carbonate fluorapatite. Bacteria, under low oxygen conditions, are thought to play a key role in the formation of modern and ancient phosphorite deposits [91, 92, 93, 94]. Changes in sea level and winnowing by currents have concentrated deposits into areas now being considered for mining. The unique combination of changing sea levels over geological time and the high surface productivity due to upwelling off the Namibian coast, for example, resulted in the formation of large areas of phosphorus-rich sediments [95, 96].

***4.6.2 Mining overview**:* A perceived future scarcity of terrestrially mined "rock phosphate" to manufacture phosphate-based fertilizer led to the present interest to mine phosphate from the ocean. The targeted deposits occur on the continental margins (both within the EEZs and extended continental shelf) of the host coastal States, in water depths varying from 50 m to 900 m. Recovery of the phosphorite will require bulk removal of the sediments just beyond the depths of maximum concentration, which can vary by locality (e.g., off New Zealand mining has been proposed to a sediment depth of at least 50 cm, and proposed to 3 meters deep off Namibia). To date, wide-head suction dredging of the seabed is proposed to pump tracts of sediment in bulk into large dredge-hopper vessels. Sorting the granules/nodules from the bulk is proposed in various ways: either vessel-transport of the entire bulk to coastal, land-processing facilities, or if phosphorites are large enough (i.e., if majority are nodules), sieving and sorting will take place onboard to collect the phosphorites, with release of unwanted bulk sediment back into the sea either at the sea surface or more likely at depth via a sinker pipe and diffuser. Some proposed mining includes further processing to fertilizer at the coastal sites, with effluent disposed into the sea.

4.6.3. Impacts from mining on habitat/resources: There have been a limited number of studies of the impacts or potential impacts of phosphorite mining and processing on the marine environment published in the scientific literature (e.g., [97, 98, 99]. However, recent interest in phosphorite deposits off Namibia, South Africa, New Zealand and Mexico has resulted in a large number of studies assessing the various potential impacts resulting from phosphorite mining, which are published as EIA reports (Namibia - http://www.namphos.com/, New Zealand - http://www.epa.govt.nz/EEZ/chatham_rock_phosphate). An overarching impact is the total removal of large areas of seabed for continuous mining effort over many years (e.g., 30 km^2 annually over at least 15 years has been proposed off New Zealand). This scale of mining is likely to have more important long-term ecosystem impacts than recognizable short-term point impacts. For phosphorites found in upwelling regions in organic-rich suboxic to anoxic sediments, excavation and exposure of such sediments pose a special set of risks to these ecosystems.

The most significant impacts from phosphate mining are likely those associated with: (i) large-scale excavation and removal of soft sediment and hard substrates (e.g. large nodules on sediment surface), affecting benthic community composition and abundance, as well as recovery rates of sediment stratification, sediment biogeochemistry and rates of faunal repopulation; (ii) long-term and continual sediment plumes, both from mining excavation and processing, that could adversely affect ecosystem functioning of both benthic and pelagic components; (iii) disruption of important fish areas: not only fishing grounds but breeding, spawning and nursery areas of both commercial and non-commercial species; (iv) contamination of coastal waters from both a) exposure of deep anoxic and metal-rich sediments to the overlying water column and b) processing effluent returned to the sea; and (v) the possibility of large-scale sediment removal and redistribution leading to tipping points regarding tolerances of both benthic and pelagic sea life to physical and chemical parameters such as dissolved oxygen, turbidity, and organic matter content of the sediment which could lead to ecosystem regime shifts. There is significant concern about displacement of species of commercial demersal fish leading to food-web disturbances [100] and combined impacts on food-safety levels for consumption and marketing resulting from release of contaminants (e.g., cadmium, uranium) from sediments and disposal of processing waste.

4.6.4 Special features that affect significance of predicted impacts: Management of phosphorite mining may require different considerations from the management of other seabed mining because most phosphorite deposits fall within the exclusive economic zones (EEZs) or extended continental shelves of States, and are therefore governed under national law. These deposits fall in areas that are close to shore and are subject to sometimes intense use by humans for fishing, oil and gas extraction, shipping and by endangered marine mammals, turtles and seabirds for migration, mating, feeding and reproduction. Thus these areas may contain more ecologically sensitive species and habitats and may be more susceptible to cumulative impacts than those discussed previously [101].

(1) Continual large-scale mining activities will be necessary to make mining operations economical. ***This scale of activity will disturb large areas of the seafloor and could generate a continual sediment plume with multiple potentially harmful effects throughout the water column, which, if severe, could lead to serious harm through wholesale, significant adverse ecosystem change.***

(2) Mining areas coincide with many highly productive areas (e.g., upwelling regions) that are of high conservation value for marine mammals, seabirds, and sensitive habitats such as deep-water coral and sponge beds that may be protected by law. ***Damage to organisms or habitats of high conservation status and with valuable ecosystem services may represent significant adverse change causing serious harm.***

(3) Highly productive areas where phosphorite deposits are found are often areas of high priority for other commercial activities such as fishing. ***Therefore, there is direct conflict with other***

commercial activities that rely on healthy ecosystem functioning and the potential for cumulative effects that cause serious harm, resulting from at least two forms of disturbance.

(4) Upwelling areas, and other areas of high productivity, are acknowledged as highly variable environments. ***Natural high spatial and temporal variability make it difficult to determine significant adverse change without extensive baseline data and sophisticated monitoring in these areas, which are lacking currently.***

(5) Phosphorites can occur in upwelling areas of low oxygen (e.g., the margins of Namibia, South Africa, Peru or Mexico) where the ecosystems are already stressed. ***Low oxygen levels slow ecosystem recovery following disturbance. Increased oxygen demand from mining activities could cross tipping points for biota in the area, enhancing the likelihood of serious harm through significant adverse impacts from mining activity.***

(6) The low-oxygen, high-sulphide conditions associated with some phosphorites also host an array of microbes with genetic potential to function on under extreme conditions. **Mining impacts may cause loss of genetic diversity with unknown biotechnology value.**

4.6.5 Actions toward understanding significant impacts of phosphorite extraction.

- Additional information is needed on microbial and faunal composition, connectivity, temporal dynamics and recovery potential of the biota associated with phosphorites of different sizes and textures. Both soft-sediment and hard-substrate faunas, and their ecological functions and ecosystem services require characterization.
- Given the proximity to coastal activities, interactions with, and cumulative impacts from, other ecosystem services associated with commercial fisheries, genetic resource potential, endangered and threatened species migration and habitation need to be addressed as a priority, as these provide direct vital services to the States concerned.

4.7 Significant effects: Cumulative impacts.

Mining site impacts may be multifaceted, resulting in cumulative impacts in a setting or region, where the effect of more than one stressor can result in a magnified impact than the stressors taken individually [18]. Knowledge of cumulative impacts will inform the determination of serious harm across multiple sectors, and is essential to development of strategic environmental assessments and management plans. Cumulative impacts can occur at many levels: (i) multiple mining operations (by one or more contractors) within a sector and region (such as in the CCZ); (ii) multiple impacts from different mineral resource sectors; and (iii) overlapping impacts from non-mining sectors that coincide with mining impacts (e.g., fisheries), including stressors related to climate change and pollution. Evaluation of cumulative impacts should include past, present and reasonably foreseeable future impacts. Estimating the magnitude of the impact of cumulative mining activities within a region is difficult with current knowledge, in part because of limited knowledge of the scales over which ecosystem structure and function play out. Unknowns include for example, the size, composition and distribution of source populations that will provide the larvae, juveniles and motile adults and dispersal potential of the source organisms available for recolonization and population recovery [102].

An additional challenge is knowing the nature and extent of all relevant activities and sources of change other than the targeted mining activity. The impacts from non-mining sectors, including oil and gas extraction, tourism, fishing, shipping, submarine cables, waste disposal, marine litter, chemical pollution, natural products, or research may be deemed acceptable individually, but when taken together with deep seabed mining can create significant impacts. For example, phosphorite lease claims in the national waters of Namibia and Mexico intersect key habitat or nursery grounds essential to local fishes, while off New Zealand the phosphorite claims overlapped a marine protected area, one of a number of closed areas instigated by the fishing industry [103]. Another example comes from Papua New Guinea where submarine tailings placement from terrestrial mining [104] may potentially interact with those of seabed mining for SMS. Although the locations and water depths of seabed mining and other activities may not coincide, the physical transport of plumes and ontogenetic migrations of larvae and juveniles might cause cumulative impacts on some deep-sea populations.

Finally, ocean acidification and climate change operate at both global and regional scales and can affect recovery and resilience of many of the ecosystems treated here [105, 106]. Stress from warming temperatures, ocean acidification, and ocean deoxygenation as well as altered particulate organic carbon flux or circulation patterns may differentially affect hydrothermal vent, seamount, abyssal and continental margin systems depending on their location and water depth [19, 39].

4.8 Conclusions and implications.

The paper authors have sought to understand what deep-seabed mining impacts have the potential to cause serious harm to the marine environment, harm that may among other things, invoke decisions not to mine in a specific area, not to approve a particular application for a contract to mine, to suspend or stop mining, to require adjustment of operations to avoid serious harm, and/or to provide financial compensation if harm ensues. Such an understanding should also indicate the type of impacts that mining operations should be designed to avoid (together with other proactive regulations to ensure effective protection).

While there are differences in extraction technology and methods used between different deep-seabed mineral types and projects, seabed mining actions that may cause harmful effects or serious harm across all targeted resources include: direct removal and destruction of seafloor habitat and organisms; alteration of the substrate and its geochemistry; modification of sedimentation rates and food webs; changes in substrate availability, heterogeneity and flow regimes; suspended sediment plumes; released toxins; and contamination associated with noise, light or chemical leakage during the extraction and removal processes. These impacts are expected to occur in benthic communities across hard and soft substrates and in the pelagic realm. Table 1 summarizes how these impacts relate to the potential for significant adverse change causing serious harm at sites where mining may take place for each of the mineral resources considered here.

However, there are clearly major knowledge gaps and uncertainties and these impel invocation of the precautionary approach. The application of this approach could include a clear requirement that: "Activities in the Area shall only take place if they do not cause serious harm to the marine environment", the standard envisaged by the drafters of the first set of mining regulations in 1990 ([107] article 2(2)).

To construct rules, regulations and procedures capable of ensuring effective protection of the marine environment from the harmful effects of mining activities and avoiding serious harm, a well-defined understanding of what may or may not constitute significant adverse change in deep-sea biodiversity as well as ecosystem structure and function will be needed. Such an understanding is required prior to the onset of commercial-scale mining operations to prevent long term, potentially irreversible harm. An ability to identify and quantify significant effects, and the valuation of the key ecosystem services with which they are associated, will be necessary to implement appropriate environmental impact assessments, environmental management plans and other regulations and payment regimes (including environmental damage assessment) associated with deep-seabed mining [22].

Scientific understanding about the impacts of mining will need to improve, and there are a number of national and international efforts currently underway which aim to achieve this goal, including the EU-funded MIDAS project (Managing Impacts of Deep Sea Resource Exploitation), among others. Disturbance experiments conducted in nodule provinces, on seamounts and at hydrothermal vents have to date provided valuable but limited insight into colonization and recovery rates in these realms because these relatively small-scale, low-intensity studies cannot replicate or predict mining impacts associated with exploitation, which will occur at much larger spatial scales and intensities. Nonetheless it is important to conduct both *in situ* and laboratory experiments in order that our understanding of serious harm from significant adverse change induced by deep-seabed mining improves, and ecological thresholds can be identified for use by regulatory authorities. Some States that have mineral resources of interest to companies do not yet have legal regulatory frameworks or official competency to assess or regulate marine mining (for example for phosphorites or SMS) within their EEZs. Legislation and regulatory conditions need to be instituted to complement those for other established industrial activities such as fishing.

While this article focuses on deep-seabed mining for minerals, these guidelines for identifying harmful effects and serious harm from potential significant adverse change may also help with management of future energy or bioprospecting interests in deep-seabed resource extraction. For example, there is great interest in exploring and exploiting novel chemical compounds and structures from deep-sea organisms that may prove useful for pharmaceuticals, molecular probes, enzymes, cosmetics, nutritional supplements, agrichemicals [108], bioinspired materials [109] and even climate remediation [110]. In the future, marine mining of methane hydrates as a novel energy source may also be of commercial interest [111]. Each of these commercial developments could have some adverse impacts on deep-sea ecosystems in common with those identified above, and some unique to the resource and its setting, depending on scale and intensity.

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Figure Captions.

Figure 1. Areas beyond national jurisdiction that have been claimed for minerals mining exploration.