

1 Defining “serious harm’ to the marine environment in the context of deep-seabed mining

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37 Highlights

- 38 • There is growing likelihood of minerals mining in the deep sea. (64)
- 39
- 40 • Assessing the significance of resulting environmental impacts takes on urgency. (79)
- 41
- 42 • The ISA is developing regulations for seabed mining which must prevent serious harm.
- 43
- 44 • Defining “serious harm” is critical to effective regulation of mining activities. (82)
- 45
- 46 • Deep faunal vulnerabilities derive from low growth rates, species longevity and rarity.
- 47
- 48 • Connectivity, resilience, and cumulative impacts are key to significance assessment.
- 49

50 ABSTRACT

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

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

69

70 1. Introduction

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

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

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

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

103 In this paper, which is based on a workshop held in 2014, these questions are addressed by first
104 examining current definitions that may inform our understanding of “serious harm” and the legal
105 requirements to avoid such harm. Ecological and ecosystem parameters are considered that may be
106 measured and there is a discussion of environmental thresholds and triggers for action when serious harm
107 is predicted or is otherwise likely to occur. The mineral resources are then introduced, including
108 distributions and ecological setting, the mining approach as understood at present, potential
109 environmental impacts of mining, the distinctive environmental and ecological features of the associated
110 ecosystem that inform the significance of impacts, and recommended actions to advance understanding
111 of impacts. The need to consider cumulative impacts is presented, before finally concluding with the

112 overall implications of the issues that surround assessing the significance of harm for decision-makers and
113 regulators with respect to deep-seabed mining activities. A key challenge will be to formulate regulations
114 that prevent “serious harm” as well as ensure overall effective protection of the marine environment.
115 Table 1 consolidates much of this information.

116 2. The international legal context for defining “Serious Harm”

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

131 An equally important objective as well as legal obligation under UNCLOS for both States and the ISA is to
132 ensure “effective protection” of the marine environment from “harmful effects” which may arise from
133 seabed mining activities (Article 145). For this purpose the ISA is required to adopt “appropriate rules,
134 regulations and procedures for *inter alia*, (a) the prevention, reduction and control of pollution and other
135 hazards to the marine environment, including the coastline, and of *interference with the ecological*
136 *balance of the marine environment ...* and (b) the protection and conservation of the natural resources of
137 the Area and the prevention of damage to the flora and fauna of the marine environment” (UNCLOS Art.
138 145 (a) and (b))[11]. This is in addition to other obligations in UNCLOS that call for, *inter alia*, the
139 protection and preservation of the marine environment,” and the taking of measures “necessary to
140 protect and preserve rare or fragile ecosystems as well as the habitats of depleted, threatened or
141 endangered species and other forms of marine life (UNCLOS Art. 192, 194(5)).

142 Existing ISA regulations for seabed mineral exploration of manganese nodules, SMS and cobalt-rich crusts
143 provide only a definition for “serious harm”. Under these regulations, “serious harm to the marine
144 environment” is defined to mean “any effect from activities in the Area on the marine environment which
145 represents a **significant adverse change** in the marine environment determined according to the rules,
146 regulations and procedures adopted by the Authority on the basis of internationally recognized standards
147 and practices” (ISA Regulations (nodules), [12]; ISA Regulations (sulphides); [13], ISA Regulations (crusts),
148 [14]). Such standards, as spelled out in the regulations and an Advisory Opinion by the International
149 Tribunal for the Law of the Sea, are to ensure the application of “best environmental practices and the
150 precautionary approach” ([13] Regulations 31(2); [15]).

151 The potential for serious harm entails serious consequences. As required by UNCLOS Art. 165(2)(I), the
152 Legal and Technical Commission (LTC), the ISA’s advisory body, is to, among other tasks, develop
153 recommendations to the Council, the ISA’s executive body, to disapprove mining in areas where

154 “substantial evidence indicates the risk of serious harm to the marine environment”. The LTC is also
155 empowered to develop recommendations for emergency orders during mining operations to “prevent
156 serious harm to the marine environment” (UNCLOS Art. 165 (k)). In turn, the ISA Council is required to
157 issue emergency orders, which may include orders for the suspension or adjustment of operations, to
158 prevent serious harm to the marine environment arising out of activities in the Area (UNCLOS, Art.
159 162(2)(w)).

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

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

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

175 *“The Commission shall develop and implement procedures for determining, on the basis of the best*
176 *available scientific and technical information....,whether proposed exploration activities in the Area*
177 *would have serious harmful effects on vulnerable marine ecosystems [, including seamounts and*
178 *hydrothermal vents], and ensure that, if it is determined that certain proposed exploration activities*
179 *would have serious harmful effects on vulnerable marine ecosystems, those activities are managed*
180 *to prevent such effects or not authorized to proceed.”* (ISA Regulations (nodules 31.4; sulphides
181 33.4; crusts 33.4)

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

193 In reality, assessing any changes to deep-sea ecosystems induced by mining activities is challenging at
194 best. The remoteness and expense of studying these ecosystems has resulted in major knowledge gaps
195 concerning habitat distribution (regionally and globally), ecosystem structure and function. These gaps

196 include species identities (most deep-sea species are undescribed), biodiversity, distribution patterns and
197 biogeography, community distributions, dynamics, trophic relationships, population connectivity,
198 physiological tolerances, ecosystem tolerances, and resilience.. Without this baseline information, it is
199 difficult to assess the impacts of a human activity in space and time, to determine whether these impacts
200 are enduring or transitory. The use of a systematic approach based on a robust ecological assessment of
201 the key physical, biogeographic, ecological, and biodiversity features of the deep seafloor will be useful
202 when dealing with the challenges of managing a large underexplored area [17]. Cumulative impacts of
203 multiple mining actions (in space and time) and additive perturbations from direct human activities (e.g.,
204 fishing activities, contaminants and spills), and climate-change related stressors (e.g., warming, ocean
205 acidification and deoxygenation) must also be considered when evaluating the significance of [changes to](#)
206 [and/or impacts on](#) deep-sea ecosystems [18,19].

207 3. Significant adverse change: Thresholds and triggers

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

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

228 If information is not available to set particular ecological thresholds, a suite of other indicators can be
229 used to determine the likelihood of significant adverse change and impacts, including those that address
230 species-, community- or ecosystem-level impacts. Here all three ecological levels are considered.
231 Significant species-level changes or impacts include: (i) extinction; (ii) significant decline in abundance; (iii)
232 decline in foundation species; (iv) reduction below critical reproductive density; (v) loss of source
233 populations; and/or (vi) loss of critical stepping-stone populations. Community-level impacts include (i)
234 alteration of key trophic linkages among species in a community; (ii) reduction in species diversity beyond
235 natural levels of variability; and/or (iii) regional declines in habitat heterogeneity, such as loss of entire
236 habitats or community types. At the ecosystem-level, impairment of important ecosystem functions such
237 as biomass production, nutrient recycling or carbon burial can lead to loss of major ecosystem services
238 upon which society depends. They may include loss of carbon sequestration capacity, genetic resources,

239 or fisheries production. These impacts can be evaluated in local, regional or global contexts. While the
240 concept of ecosystem services underlies many of the above indicators and metrics, threshold levels of
241 decline in services have yet to be identified. These services are likely to vary by habitat, and the spatial
242 and temporal scale at which changes are significant to the ecosystem have not been defined here.
243 Additional measures that reflect key services are needed and a quantifiable measure of lost services will
244 need to be incorporated into significance assessment [22].

245 4. Deep-seabed mining resources and potential impacts

246 4.1 Deep-seabed mining activities to date

247 As of 2016 there are 25 exploration contracts approved by the ISA: four for cobalt-rich crusts, each 3,000
248 km² in the South Atlantic and Mid-Pacific; 16 for manganese nodules, each up to 75,000 km² in the Clarion
249 Clipperton Fracture Zone in the Pacific (15) and in the Indian Ocean (1); and five for SMS, each
250 approximately 10,000 km² in the Indian Ocean and on the Mid-Atlantic Ridge (Figure 1). There also has
251 been commercial interest in deep-seabed minerals within national jurisdictions, including in the Pacific
252 Islands region, Mexico, Namibia, New Zealand, Saudi Arabia, South Africa, and Sudan. For example, many
253 deep-seabed mineral licenses for *exploration*— evaluating resources prior to the production phase of
254 mining – have been issued over recent years for SMS by Fiji², Papua New Guinea³, Solomon Islands⁴ and
255 Tonga.⁵ In August 2015, the Cook Islands invited bids for deep-seabed mineral exploration of manganese
256 nodules within its waters but none have been received.⁶ The world’s first deep-seabed mining project may
257 commence as early as 2019 in Papua New Guinea’s waters, although financial difficulties are causing
258 delays.⁷ The mining company, Nautilus Minerals Inc., was granted a mining lease in 2011 by Papua New
259 Guinea Government in the South Pacific Bismarck Sea containing SMS deposits.⁸ In 2010, Saudi Arabia and
260 Sudan granted a production license for a SMS project known as ‘Atlantis II’ in the Red Sea, managed by a
261 Saudi Arabian/Canadian consortium. However, there have been no public indications of imminent
262 intention to commence production in this site.⁹ The Namibian government has granted two mining
263 licenses (to Lev Leviev and to Namibian Marine Phosphate), but a moratorium was instituted while further
264 environmental impact assessment was conducted. As of August 2016 the official decision regarding
265 marine phosphate mining in Namibian waters had not been announced, with the matter of
266 strategically assessing the cumulative environmental impacts under review by the Government of
267 Namibia.¹⁰ As of Sept. 2016, a decision on phosphate mining in Namibian waters is still pending.
268 Exploration and mining claims for phosphorites have been made in South Africa, New Zealand
269 and Mexico, although the environmental ministries of the latter two States have recently rejected
270 these based on environmental concerns^{11,12}. It is important to note that no exploitation of deep-seabed
271 minerals has taken place yet. This situation presents an unusual opportunity for the architects of relevant
272 legal regimes, and the permitting decision-makers, to make informed decisions at the outset.

²http://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

⁵http://gsd.spc.int/dsm/public/files/2014/may/03_LepaolaVaea.pdf

⁶<http://www.seabedmineralsauthority.gov.ck/cook-islands-seabed-minerals-tender-2015>

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

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

280 **4.2 Manganese nodules**

281

282 **4.2.1 Mineral resource:** Manganese nodules (also called polymetallic nodules) are mineral precipitates of
283 manganese, iron oxides and other metals. Nodules range in size from millimeters up to a half meter or
284 more. The nodules of greatest commercial interest contain relatively high levels of nickel and copper (e.g.,
285 1.5% of the nodule weight), cobalt, zinc, and traces of other metals (e.g., molybdenum, lithium) important
286 to high-tech industries [23]. The nodules form extremely slowly (with estimated growth rates of 2-15 mm
287 per million years) and occur over extensive areas in the abyssal Pacific, Indian and Atlantic Oceans, where
288 they provide hard-substrate habitat for a variety of fauna (e.g., sponges, foraminifera). The nodules
289 currently of greatest commercial interest occur beneath the relatively low productivity environment at
290 10-20 degrees north of the equator in the Pacific Ocean in the Clarion Clipperton Zone (CCZ), within an
291 area of ~6 million km², with nodule abundances ranging from <1 to >35 kg m⁻² [23].

292 **4.2.2 Mining overview:** The extraction of manganese nodules is envisioned to be carried out by a series of
293 remotely operated, technologically advanced nodule harvesters that are likely to plough, scrape, and/or
294 vacuum the seafloor over large areas (300-800 km² of seabed per mining operation per year, [24]. As
295 envisioned by some companies (e.g., UK Seabed Minerals), crushed or whole nodules and entrained
296 sediments will be pulled up a riser pipe to the surface, where nodules will be offloaded to a production
297 support vessel for transport to land. Sediment-containing water will most likely be returned to the ocean
298 at the site at an, as yet, undetermined depth.

299 **4.2.3 Impacts from mining on habitat/resources:** Manganese nodule-mining operations could have major
300 impacts over large abyssal regions. Removal of nodules will remove specialized fauna (e.g., foraminifera
301 and sponges) that live on the nodules [25,26,27], together with organisms that live in the soft sediment
302 patches between and under the nodules [24,28]. Epifaunal densities increase with nodule density, and
303 alcyonacean and antipatharian corals are present in the CCZ only where nodules occur [29]. In addition,
304 there appears to be a high diversity of nodule-obligate megafauna in the CCZ [30]. Nodule removal,
305 sediment disturbance and plume perturbations have the potential to reduce habitat complexity,
306 biodiversity and ecosystem function over large spatial scales both at the seafloor and in the water
307 column. Some effects will likely persist for millennia because the formation of new nodules, and the
308 habitats and heterogeneity they provide, is estimated to take millions of years [29].

309

310 The nodule extracting equipment will remove and disturb the top 15-40 cm of sediment that provides
311 food for a high diversity of surface deposit-feeding organisms. The extracting equipment will likely also
312 compress seafloor sediments beyond normal conditions, adversely affecting biota living within the
313 sediments, benthic colonization and other processes (e.g., seafloor biogeochemistry; [31]. Nodule
314 collection will cause sediment plumes during discharges that may disperse at least 10s and possibly
315 hundreds of kilometers [24,27]. Such plumes have the potential to bury or smother seafloor organisms
316 and habitats, and prevent larval settlement and colonisation, because background rates of sediment
317 deposition are extremely low (e.g., [32,33]. Studies have shown negative effects from 1 cm of sediment
318 deposition in the CCZ [34], and the most food-poor area of the CCZ (NW regions in the CCZ) will most
319 likely be more sensitive to sedimentation. Plumes dispersing through the water column may clog the
320 filtering membranes of suspension-feeding fauna (both benthic and pelagic). Resuspended sediments may
321 also release oxygen-depleted pore waters and chemicals (e.g., heavy metals from the sediment) with

322 potential biogeochemical or ecotoxicological effects [35], and could affect vision, feeding and
323 communication processes (e.g., bioluminescence) in the pelagic environment. The chronic effects of
324 recurrent sediment plumes within an abyssal mining region remain unstudied but could be deleterious in
325 regions such as the abyssal CCZ where natural sediment resuspension has not been documented and
326 appears very unlikely based on observations and measurements [36].
327

328 Waste materials from initial at-sea separation are expected to be released through a discharge pipe into
329 the middle of the water column or at the water/seafloor interface, but the resulting sediment plumes may
330 also cause impacts on midwater and mesopelagic species in the water column. Suspended particle effects
331 on feeding, prey avoidance, and other ecological processes are likely but unstudied. In addition, biota
332 throughout the water column might be affected by sediment leakage from the system used to lift the
333 nodules to the surface, and sediment runoff from the mining support vessel could have local impacts on
334 photosynthetic productivity in surface waters.
335

336 In addition to physical impacts caused by mining, sound from mining machines, pumps, platforms and
337 vessels may occur at the sediment-water interface, mid-depth water column and surface water column.
338 Anthropogenic sound is known to cause harmful effects to marine mammals [37], but impacts on lower
339 trophic level organisms are poorly understood, even in shallow-water environments. In addition to
340 sound, light from mining operations may blind, attract, or misdirect organisms, altering their visual
341 capabilities, communications, mate finding or prey avoidance capacity [38].
342

343 **4.2.4 Special features that affect significance of predicted impacts:** Several traits characterize abyssal
344 habitats where nodules are found that are key to understanding the significance of predicted impacts and
345 recovery potential of affected ecosystems, and thus the potential for mining to inflict ‘serious harm’.
346

347 (1) Manganese nodules are found underlying mesotrophic/oligotrophic water masses and the fauna
348 inhabiting the water column and seafloor in these regions generally exist under extremely stable
349 physical conditions (including low sedimentation rates, low current velocities and few/no resuspension
350 events over decade to century time scale). **Therefore, extensive resuspension and deposition of
351 sediments over large spatial scales will cause a substantial change to the existing ecosystem, with
352 harmful effects. Some of these changes may be sufficiently widespread to constitute serious harm to
353 vulnerable marine ecosystems and/or to the wider marine environment.**
354

355 (2) Abyssal ecosystems in the CCZ are very food poor, with biomass, community structure, production,
356 growth rates, and recolonization rates all controlled by the very low flux of particulate organic material
357 sinking from the distant euphotic zone [39]. **Therefore, ecosystem recovery rates from mining
358 disturbance will be very slow, so impacts on the sediment-dwelling biota from single mining
359 activities may persist for decades to centuries, causing harmful effects.**
360

361 (3) Manganese nodules provide much of the available hard substrate in the deep waters of the CCZ and
362 other abyssal plains regions, and nodules can take millions of years to form [40]. **Nodule removal will
363 eliminate much of this habitat, as well as the specialized nodule fauna** [29]. Surveys conducted in the
364 CCZ along tracks from trawling or experimental mining simulations up to 37 years old suggest that
365 epifauna is almost completely absent and recovery of the ecosystem in this area is slow [29]. **Complete
366 removal of nodules will cause significant adverse change for long periods of time (millennia),
367 possibly over areas hundreds of km in extent.**
368

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

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- (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.***

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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.

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4.3 Seafloor massive sulphides

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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 megafaunal 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].

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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.

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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,

423 prospective mine sites often contain both active and inactive deposits, and so the vulnerability of
424 communities at both will need to be assessed.

425 **4.3.2 Mining overview:** Existing concepts for SMS mining envision the use of multiple remotely operated,
426 large, technologically advanced machines to undertake open-pit mining once the sediment overburden is
427 removed [51]. The machines will cut, crush, and gather the ore and then send it as slurry to the
428 production support vessel via an enclosed riser and lifting system. Once on board the mining support
429 vessel, the slurry will be dewatered to collect all but the finest particles (to ~10 µm), then seawater and
430 fine particles will be discharged back into the sea at a depth close to the seabed. The ore will be
431 transported to land for further processing. While single mining sites may cover local areas as small as 100
432 m²; multiple sites in close proximity are likely to be mined, thus introducing cumulative harm within the
433 exploited region that should be considered in assessing significant adverse impact.

434 **4.3.3 Impacts from mining on habitat/resources**

435 **4.3.3.1 Active vents.** SMS mining operations will have a direct impact on the mining site, removing the
436 substratum and its associated fauna and thus reducing diversity at all levels: genetic, species, functional,
437 and habitat [38,43,52] and causing serious harm. The 3-dimensional structure of the habitat will be
438 flattened, reducing habitat heterogeneity to a minimum and changing the substratum characteristics
439 (e.g., porosity, particle size distribution, mineralogy), as well as the geochemical and hydrodynamic
440 regimes [38,50]. High turbidity plumes with elevated metal concentrations generated by the mining
441 activity and from the return into the sea of the water that has been separated from the ore material on-
442 vessel [53] could affect pelagic and benthic populations downstream, potentially impeding vision,
443 reducing bioluminescence, clogging organs of filter- and particle-feeders, disrupting larval development
444 and settlement and potentially resulting in toxic effects from bioaccumulation of metals [27,43]. As with
445 manganese nodule mining, light and noise from seabed activities may cause additional impacts. At active
446 sites, these physico-chemical impacts will likely be temporary, since venting is expected to persist and
447 new chimneys will precipitate and coalesce [54]. Local fauna will be crushed by the mining operations
448 (sessile and slow moving fauna) or dispersed to other areas (mobile fauna such as fish and some large
449 crustaceans), thus reducing biodiversity and abundance totally or to very low levels, in the absence of
450 mitigation. This direct impact is particularly of concern for vent-endemic and rare species. At fast- and
451 intermediate-spreading ridges, active vent communities are known to recover from catastrophic impacts
452 (volcanic eruptions) on a decadal time scale [38]. The rate of recovery following a catastrophic
453 disturbance at active vents on slow- or ultra-slow spreading ridges or in back-arc basins is unknown.

454
455 **4.3.3.2 Inactive vents.** A single mining event at an inactive vent will eliminate local fauna and cause harm,
456 but the extent to which this fauna is endemic is unknown. If the fauna of inactive vents is also found on
457 hard substrata throughout a ridge system, the severity of the impact is considerably lessened in terms of
458 lost biodiversity. However, where populations of particular taxa are relatively large at inactive vent sites,
459 these populations could be disproportionately important for the maintenance of populations elsewhere
460 through the supply of larval recruits. Recovery of inactive vents from mining activities is not known –in
461 fact the fauna of inactive vents is hardly known [45, 49]– but is presumed to be slow, on the order of
462 decades to centuries [38, 46]. To assess the potential for such recovery of populations and communities, a
463 sound understanding of regional species distributions, their genetic diversity, reproductive ecology, and
464 dispersal potential, as well as regional hydrodynamic regime that will drive dispersal of larvae, resulting
465 gene flow and colonisation, is necessary. This must be placed within the context of temporal dynamics,
466 natural variation, and succession of indicator species [52].

467
468 At inactive sites, mining will remove the vertical topography, and modify seafloor texture and habitat
469 heterogeneity; this will likely be a permanent effect at inactive sites, barring reactivation of fluid flow. If
470 an inactive vent becomes active [55], once the ore is removed, the local physiography, biodiversity, and
471 connectivity would be changed and could be enhanced.

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474 **4.3.4 Special features that affect the significance of predicted impacts at vents:**

475 **4.3.4.1 Active vents.** Because active vents are naturally dynamic (including becoming inactive and subject
476 to destructive volcanic eruptions), the fauna exhibit fast growth rates and high reproductive output, that
477 may make them resilient to major disturbances. However, other attributes may make them particularly
478 susceptible to cumulative impacts of multiple mining events in a region and have led to their listing as
479 indicators of Vulnerable Marine Ecosystems [16]. Several characteristics distinguish active hydrothermal
480 vents from most other habitats in the marine biome [56, 57, 58] and are key to understanding the
481 significance of predicted impacts and recovery potential of affected ecosystems, and thus the potential
482 for mining to inflict a significant adverse impact and ‘serious harm’:

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

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

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

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

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

511 **4.3.4.2 Inactive vents:**

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

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

- 521 3) Inactive vent sites of interest for mining may exist in close proximity to (or be interspersed with),
522 active vent sites, and fauna may benefit from the higher productivity associated with the active
523 venting. This increased food availability may support relatively large populations of filter/suspension-
524 feeding fauna such as corals, which are often long-lived. **Therefore, community recovery rates at**
525 **inactive sites may be long (e.g., hundreds of years), and mining disturbance could also cause**
526 **significant adverse change to the connectivity of those taxa that rely disproportionately on larval**
527 **supply from large populations at inactive vent sites.**
- 528 4) Plumes generated by mining activities will be enriched in toxic metals. **If these toxic metals become**
529 **bioavailable, could have a harmful effect on the biota (pelagic and benthic) in the plume shadow**
530 **and through bioaccumulation. The extent to which bioavailability of toxic metals could become a**
531 **significant adverse impact is not known.**

532
533 **4.3.5 Actions toward understanding whether there will be significant adverse impacts of SMS extraction**
534 **at active hydrothermal vents and inactive sulphide deposits.**

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

552 **4.4 Cobalt-rich crusts**

553 **4.4.1 Mineral resource:** Cobalt-rich crusts (also called polymetallic crusts) form a thin mineral layer
554 through precipitation over millions of years from the surrounding seawater, and accumulate on
555 hardground areas of seafloor swept clear of sediments by current flow [40,60]. The thickest deposits (up
556 to 25 cm) occur on the summits and flanks of seamounts (especially large flat-topped guyots), ridges and
557 plateaus, fused to the basal rock. These features occur in all oceans of the world, but are most common in
558 the Pacific Ocean, where there are estimated to be at least 50,000 seamounts and knolls [61]. The main
559 constituents of the crusts are iron and manganese, although many other minerals occur in smaller
560 amounts. The metals of commercial interest in cobalt-rich crusts are cobalt, nickel and manganese, and
561 are most enriched at water depths of 800 to 2500 m [62]. The crusts also contain rare-earth elements [40,
562 63].

563 **4.4.2 Mining overview:** The mining of cobalt-rich crusts is more technologically complex than for
564 manganese nodules (which occur on/in soft sediments) or SMS (which protrude from the seafloor in
565 brittle structures) [51]. Although it will similarly require the use of large, remotely operated,
566 technologically advanced machinery to dig into and cut, crush and gather the ore, and send it as slurry to
567 the production support vessel through a riser and lifting system, or as whole rock material in a chain of
568 bucket-type containers. The variable thickness of the crusts combined with the steep and rugged
569 seamount terrain makes design and operation of the collection tools difficult. However, once on board
570 the vessel, the processes are similar to the other mineral types. Slurry will be dewatered, the seawater

571 and discard products will be discharged back into the sea and the ore transported to land for processing
572 [51]. A mining-site model developed by Hein et al. [64], and endorsed by the ISA in its cobalt-rich crust
573 regulations, involves a combination of 20 km² sites and a total area of about 260 km² over a 20-year
574 mining life span. Subsequently, He et al. [65] suggested that to be profitable a mine site would need to
575 cover a total area of 1,214 km², and be mined for 20 years to produce 1 million wet tons. This form of
576 mining would require multiple mining sites on multiple seamounts in close proximity, and would cause
577 cumulative impacts within the exploited region.

578 **4.4.3 Impacts from mining on habitat and resources:** Extraction of cobalt-rich crusts will cause impacts at
579 the seafloor, through the water column, and potentially at the ocean surface [66]. The most direct and
580 substantial effects will be on the habitats and benthic fauna at the seafloor. Here there will be substantial
581 physical alteration of the seafloor as the crust is removed, the overall relief of the surface of the
582 seamount will be flattened to an extent, and the amount of soft sediment will increase. Hence there is
583 expected to be reduction in habitat heterogeneity, and changes in the geochemical characteristics of
584 seafloor sediments. Seamounts often have high diversity and density of large, sessile animals, such as
585 sponges and corals, as well as giant protozoans called xenophyophores, which form a biogenic habitat for
586 other communities [67,68,69]. These organisms will be affected directly by the mining operations, and will
587 not survive. Mobile animals, such as fish and crustaceans, may be able to disperse to other areas, but the
588 overall biodiversity at the mining site will be reduced to very low levels. These impacts are particularly
589 important for endemic and rare species. The capacity of affected communities to recover may be low.
590 Typically, deep-sea invertebrate and fish species are long-lived and have slow growth rates, and their
591 ability to recover from human disturbance (such as fishing or mining) is very low [70,71]. The potential for
592 recovery will be affected by substrate changes, with soft sediment from mining plumes being unsuitable
593 for many sessile species, and potentially smothering small animals and clogging the feeding structures of
594 suspension feeders. The availability of source populations on nearby seamounts that will provide the
595 necessary propagules (larvae, juveniles and dispersing adults) is poorly understood. Hence, both physical
596 and biogenic habitat will be severely impacted over a long period of time (likely many decades to
597 centuries for the fauna).

598
599 Mining for cobalt-rich crusts will generate plumes of sediment, both from the physical disturbance of the
600 seafloor, and from any discharge of processing waste. This sediment will have direct impacts on benthic
601 communities through smothering and burying of animals, clogging of feeding structures, preventing larval
602 settlement and colonisation, and indirectly through metal release and accumulation through the food
603 chain. The vigorous hydrodynamic regime on seamounts suggests that the “downstream” extent of
604 sediment plume impacts could reach well beyond the direct site of mining, over 100s of meters [72].
605 Depending on the discharge depth of waste water (including fines, and small rocks), there can be impacts
606 on plankton and fish communities throughout the water column. Effects include: potential oxygen
607 depletion; nutrient and trace metal enrichment; changes in water clarity affecting visual predators;
608 behavioural changes of plankton, mesopelagic fish and marine mammals from the plume density,
609 contaminant composition, and associated noise; bioaccumulation of toxic metals in higher predators;
610 toxic effects for early life history stages (e.g., larvae), and direct mortality of small plankton and
611 mesopelagic fish [73].

612
613 **4.4.4 Special features that affect significance of predicted impacts:** Limited biological survey work has
614 been directed specifically at cobalt-rich crust habitats, but many studies have occurred on seamounts that
615 are known to have such crusts. From these a number of key biodiversity characteristics can be defined
616 (after [66,74,75]) that are important for understanding the significance of impact and recovery potential of
617 seamount ecosystems.

618
619 (1) The dominant benthic fauna on seamounts are often sessile corals and sponges, which can form
620 dense reef-like structures [76], and be much more abundant on seamounts than on continental
621 slope habitats (e.g., [77]). The complexity and fragility of these taxa make them highly
622 vulnerable to impact by mining operations. These corals and sponges provide important food,

623 habitat and refuge for a large number for associated invertebrates and fish species (e.g.,
624 [78,79,80]. **Hence loss of the main components of many cobalt-rich crust benthic communities**
625 **will have a follow-on effect to other associated species, causing serious harm through**
626 **significant adverse change.**

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

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

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

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

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

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

670

671 **4.4.5 Actions toward understanding significant impacts of cobalt-rich crust extraction.**

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

680 **4.6 Phosphorites**

681 **4.6.1 Mineral resources:** Phosphorites (also called phosphates) are widely distributed in the marine
682 environment, mainly in outer shelf and upper slope unconsolidated sediments on continental margins,
683 and particularly along boundary upwelling areas where their biogenic origin is linked to organic-rich
684 surface sediments [86, 88]. Rich phosphorite deposits are found in the Benguela, Humboldt, California
685 and Canary upwelling systems, off the west coast of India, and off the southern and western shelf of
686 South Africa. Other phosphorite deposits not linked to present-day upwelling (but including regions of
687 high productivity) are found off the east coast of North America, off Australia and New Zealand and at
688 several island sites in the Pacific and Indian Oceans [5,85,89,90]. The character of the deposit varies with
689 locality, from small granules <500 µm, to lamellae, crusts, concretions and nodules several centimeters in
690 diameter. Deposits are concentrated at varying depths within surface sediments.

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

698 **4.6.2 Mining overview:** A perceived future scarcity of terrestrially mined “rock phosphate” to
699 manufacture phosphate-based fertilizer led to the present interest to mine phosphate from the ocean.
700 The targeted deposits occur on the continental margins (both within the EEZs and extended continental
701 shelf) of the host coastal States, in water depths varying from 50 m to 900 m. Recovery of the
702 phosphorite will require bulk removal of the sediments just beyond the depths of maximum
703 concentration, which can vary by locality (e.g., off New Zealand mining has been proposed to a sediment
704 depth of at least 50 cm, and proposed to 3 meters deep off Namibia). To date, wide-head suction
705 dredging of the seabed is proposed to pump tracts of sediment in bulk into large dredge-hopper vessels.
706 Sorting the granules/nodules from the bulk is proposed in various ways: either vessel-transport of the
707 entire bulk to coastal, land-processing facilities, or if phosphorites are large enough (i.e., if majority are
708 nodules), sieving and sorting will take place onboard to collect the phosphorites, with release of
709 unwanted bulk sediment back into the sea either at the sea surface or more likely at depth via a sinker
710 pipe and diffuser. Some proposed mining includes further processing to fertilizer at the coastal sites, with
711 effluent disposed into the sea.

712 **4.6.3. Impacts from mining on habitat/resources:** There have been a limited number of studies of the
713 impacts or potential impacts of phosphorite mining and processing on the marine environment published

714 in the scientific literature (e.g., [97, 98, 99]). However, recent interest in phosphorite deposits off Namibia,
715 South Africa, New Zealand and Mexico has resulted in a large number of studies assessing the various
716 potential impacts resulting from phosphorite mining, which are published as EIA reports (Namibia -
717 <http://www.namphos.com/>, New Zealand - http://www.epa.govt.nz/EEZ/chatham_rock_phosphate). An
718 overarching impact is the total removal of large areas of seabed for continuous mining effort over many
719 years (e.g., 30 km² annually over at least 15 years has been proposed off New Zealand). This scale of
720 mining is likely to have more important long-term ecosystem impacts than recognizable short-term point
721 impacts. For phosphorites found in upwelling regions in organic-rich suboxic to anoxic sediments,
722 excavation and exposure of such sediments pose a special set of risks to these ecosystems.

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

739 **4.6.4 Special features that affect significance of predicted impacts:** Management of phosphorite mining
740 may require different considerations from the management of other seabed mining because most
741 phosphorite deposits fall within the exclusive economic zones (EEZs) or extended continental shelves of
742 States, and are therefore governed under national law. These deposits fall in areas that are close to shore
743 and are subject to sometimes intense use by humans for fishing, oil and gas extraction, shipping and by
744 endangered marine mammals, turtles and seabirds for migration, mating, feeding and reproduction. Thus
745 these areas may contain more ecologically sensitive species and habitats and may be more susceptible to
746 cumulative impacts than those discussed previously [101].

- 747 (1) Continual large-scale mining activities will be necessary to make mining operations economical.
748 ***This scale of activity will disturb large areas of the seafloor and could generate a continual***
749 ***sediment plume with multiple potentially harmful effects throughout the water column, which,***
750 ***if severe, could lead to serious harm through wholesale, significant adverse ecosystem change.***
751 (2) Mining areas coincide with many highly productive areas (e.g., upwelling regions) that are of high
752 conservation value for marine mammals, seabirds, and sensitive habitats such as deep-water
753 coral and sponge beds that may be protected by law. ***Damage to organisms or habitats of high***
754 ***conservation status and with valuable ecosystem services may represent significant adverse***
755 ***change causing serious harm.***
756 (3) Highly productive areas where phosphorite deposits are found are often areas of high priority for
757 other commercial activities such as fishing. ***Therefore, there is direct conflict with other***

- 758 *commercial activities that rely on healthy ecosystem functioning and the potential for*
759 *cumulative effects that cause serious harm, resulting from at least two forms of disturbance.*
- 760 (4) Upwelling areas, and other areas of high productivity, are acknowledged as highly variable
761 environments. **Natural high spatial and temporal variability make it difficult to determine**
762 **significant adverse change without extensive baseline data and sophisticated monitoring in**
763 **these areas, which are lacking currently.**
- 764 (5) Phosphorites can occur in upwelling areas of low oxygen (e.g., the margins of Namibia, South
765 Africa, Peru or Mexico) where the ecosystems are already stressed. **Low oxygen levels slow**
766 **ecosystem recovery following disturbance. Increased oxygen demand from mining activities**
767 **could cross tipping points for biota in the area, enhancing the likelihood of serious harm**
768 **through significant adverse impacts from mining activity.**
- 769 (6) The low-oxygen, high-sulphide conditions associated with some phosphorites also host an array
770 of microbes with genetic potential to function on under extreme conditions. **Mining impacts may**
771 **cause loss of genetic diversity with unknown biotechnology value.**

772

773 **4.6.5 Actions toward understanding significant impacts of phosphorite extraction.**

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

782 **4.7 Significant effects: Cumulative impacts.**

783 Mining site impacts may be multifaceted, resulting in cumulative impacts in a setting or region, where the
784 effect of more than one stressor can result in a magnified impact than the stressors taken individually
785 [18]. Knowledge of cumulative impacts will inform the determination of serious harm across multiple
786 sectors, and is essential to development of strategic environmental assessments and management plans.
787 Cumulative impacts can occur at many levels: (i) multiple mining operations (by one or more contractors)
788 within a sector and region (such as in the CCZ); (ii) multiple impacts from different mineral resource
789 sectors; and (iii) overlapping impacts from non-mining sectors that coincide with mining impacts (e.g.,
790 fisheries), including stressors related to climate change and pollution. Evaluation of cumulative impacts
791 should include past, present and reasonably foreseeable future impacts. Estimating the magnitude of the
792 impact of cumulative mining activities within a region is difficult with current knowledge, in part because
793 of limited knowledge of the scales over which ecosystem structure and function play out. Unknowns
794 include for example, the size, composition and distribution of source populations that will provide the
795 larvae, juveniles and motile adults and dispersal potential of the source organisms available for
796 recolonization and population recovery [102].

797 An additional challenge is knowing the nature and extent of all relevant activities and sources of change
798 other than the targeted mining activity. The impacts from non-mining sectors, including oil and gas
799 extraction, tourism, fishing, shipping, submarine cables, waste disposal, marine litter, chemical pollution,
800 natural products, or research may be deemed acceptable individually, but when taken together with deep
801 seabed mining can create significant impacts. For example, phosphorite lease claims in the national

802 waters of Namibia and Mexico intersect key habitat or nursery grounds essential to local fishes, while off
803 New Zealand the phosphorite claims overlapped a marine protected area, one of a number of closed
804 areas instigated by the fishing industry [103]. Another example comes from Papua New Guinea where
805 submarine tailings placement from terrestrial mining [104] may potentially interact with those of seabed
806 mining for SMS. Although the locations and water depths of seabed mining and other activities may not
807 coincide, the physical transport of plumes and ontogenetic migrations of larvae and juveniles might cause
808 cumulative impacts on some deep-sea populations.

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

814 4.8 Conclusions and implications.

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

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

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

836 To construct rules, regulations and procedures capable of ensuring effective protection of the marine
837 environment from the harmful effects of mining activities and avoiding serious harm, a well-defined
838 understanding of what may or may not constitute significant adverse change in deep-sea biodiversity as
839 well as ecosystem structure and function will be needed. Such an understanding is required prior to the
840 onset of commercial-scale mining operations to prevent long term, potentially irreversible harm. An
841 ability to identify and quantify significant effects, and the valuation of the key ecosystem services with
842 which they are associated, will be necessary to implement appropriate environmental impact

843 assessments, environmental management plans and other regulations and payment regimes (including
844 environmental damage assessment) associated with deep-seabed mining [22].

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

859 While this article focuses on deep-seabed mining for minerals, these guidelines for identifying harmful
860 effects and serious harm from potential significant adverse change may also help with management of
861 future energy or bioprospecting interests in deep-seabed resource extraction. For example, there is great
862 interest in exploring and exploiting novel chemical compounds and structures from deep-sea organisms
863 that may prove useful for pharmaceuticals, molecular probes, enzymes, cosmetics, nutritional
864 supplements, agrichemicals [108], bioinspired materials [109] and even climate remediation [110]. In the
865 future, marine mining of methane hydrates as a novel energy source may also be of commercial interest
866 [111]. Each of these commercial developments could have some adverse impacts on deep-sea ecosystems
867 in common with those identified above, and some unique to the resource and its setting, depending on
868 scale and intensity.

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1228 **Figure Captions.**

1229 **Figure 1. Areas beyond national jurisdiction that have been claimed for minerals mining exploration.**

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