Marine Policy 138 (2022) 105006

Contents lists available at ScienceDirect

Marine Policy

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

Assessment of scientific gaps related to the effective environmental management of deep-seabed mining

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ARTICLE INFO

Keywords:
Deep-sea mining
Hydrothermal vents
Cobalt-rich ferromanganese crusts
Polymetallic nodules

ABSTRACT

A comprehensive understanding of the deep-sea environment and mining's likely impacts is necessary to assess whether and under what conditions deep-seabed mining operations comply with the International Seabed Authority's obligations to prevent 'serious harm' and ensure the 'effective protection of the marine environment from harmful effects' in accordance with the United Nations Convention on the Law of the Sea. A synthesis of the

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https://doi.org/10.1016/j.marpol.2022.105006
Received 24 August 2021; Received in revised form 10 February 2022; Accepted 12 February 2022

Seamounts
Polymetallic sulfides
Policy
International Seabed Authority

peer-reviewed literature and consultations with deep-seabed mining stakeholders revealed that, despite an increase in deep-sea research, there are few categories of publicly available scientific knowledge comprehensive enough to enable evidence-based decision-making regarding environmental management, including whether to proceed with mining in regions where exploration contracts have been granted by the International Seabed Authority. Further information on deep-sea environmental baselines and mining impacts is critical for this emerging industry. Closing the scientific gaps related to deep-seabed mining is a monumental task that is essential to fulfilling the overarching obligation to prevent serious harm and ensure effective protection, and will require clear direction, substantial resources, and robust coordination and collaboration. Based on the information gathered, we propose a potential high-level road map of activities that could stimulate a much-needed discussion on the steps that should be taken to close key scientific gaps before any exploitation is considered. These steps include the definition of environmental goals and objectives, the establishment of an international research agenda to generate new deep-sea environmental, biological, and ecological information, and the synthesis of data that already exist.

1. Introduction

As countries increasingly look to the ocean as a frontier for economic development, plans to exploit minerals from the deep seabed are gathering pace [1]. In areas beyond national jurisdictions (ABNJ), extraction of mineral resources at the seafloor is managed by the International Seabed Authority (ISA), an organization established by the United Nations Convention on the Law of the Sea (UNCLOS) to organize, regulate, and control seabed mining on behalf of humankind. This management is grounded in the principle that holds the seabed in ABNJ to be the Common Heritage of Mankind. In accordance with UNCLOS (Article 145 and 162), the ISA must, among other things, prevent ‘serious harm’ and ensure the ‘effective protection of the marine environment’ from harmful effects, which may occur from seabed-mining activities [2,3].

Assessing whether these environmental obligations will be fulfilled requires a comprehensive understanding of the deep marine environment, including environmental baseline conditions, and mining’s likely impacts. Yet our scientific knowledge remains nascent due to limited exploration of the deep ocean given its vast size and inaccessibility [4–8]. Before any regulations are adopted and exploitation contracts are awarded in ABNJ, there should be enough information to make science-based and data-driven decisions.

This study therefore sought, via a literature review and stakeholder consultation, to determine the crucial scientific gaps that should be resolved by the ISA and international community to enable evidence-based decision-making about seabed mining in ABNJ. This includes gaps in scientific information needed to develop a robust and comprehensive environment impact assessment and statement (EIA/EIS), formulate an environmental monitoring and management plan (EMMP), and enable the ISA to optimize its role as an effective regulator, including, among other things, the designation of area-based management tools, development of regional environmental management targets and thresholds, rigorous assessment of contractor applications and performance, and commissioning of strategic scientific studies at a regional level. Based on the information gathered, the authors also propose a potential high-level “road map” to stimulate a discussion on the steps that could be taken to address those scientific gaps before any exploitation occurs.

2. Methods

Data collection consisted of (1) a review and synthesis of peer-reviewed literature and (2) a stakeholder consultation. Information amassed was assimilated and synthesized to inform the scientific gaps assessment and propose solutions for closing the gaps.

2.1. Review of peer-review literature

Using Google Scholar, we searched for peer-reviewed articles written in English from 2010 onward that contained various iterations of the term “deep-seabed mining”. Earlier articles, as well as those written in languages other than English, were excluded from the initial search to control the number of articles returned while including the most recent research. By constraining our search of peer-reviewed articles to this timeframe, we acknowledge that some of the information in earlier articles will not be reflected in our results; however, the articles we reviewed, synthesized, and discussed, built upon those earlier works, and are therefore not absent from our analysis. This review is also primarily based on information that is publicly available, limiting evaluation of contractor environmental baseline data and conceptual designs of mining technology that are currently confidential.

Resulting articles, as well as articles suggested by participants during the stakeholder consultation, were reviewed for information relevant to two key questions:

1) What is known and unknown about the deep-sea environments and fauna where seabed mining may take place?
2) What is known and unknown about the impacts of deep-seabed mining and its management?

A total of 306 relevant articles were qualitatively summarized, and from those summaries, responses to both questions were prepared, subdivided by (i) resource type (polymetallic nodules, polymetallic sulfides, and cobalt-rich ferromanganese crusts) [9]; and (ii) geographic region. Scientific gaps were assessed at the regional scale and not at the level of an individual mine site. It is possible that knowledge levels may be greater at the individual mine-site scale for some categories, however without public access to all environmental data derived from individual contractors, this remains unclear. In addition, decisions on the knowledge levels for many categories at the scale of an individual mine site will be contingent upon regional assessments, such as species distribution, population connectivity, and species contribution to ecosystem functions, which will inform the potential for loss of biodiversity and disruption of ecosystems functions and services under varying mining intensities.

Categories relevant to understanding environmental baselines (the first question) were: abiotic (bathymetry, oceanographic setting, seabed properties, natural disturbance regimes) and biotic (species taxonomy, trophic relationships, life histories, spatial and temporal variability, connectivity, and ecosystem functions and services in the deep sea) [10]. Categories relevant to understanding seabed-mining management (the second question) were: anticipated deep-seabed mining impacts, environmental resilience, and potential management measures. Impacts were subdivided into: removal of resources, substrate and fauna, sediment plumes from benthic disturbance and return water, the release of chemical substances and toxicity, increases in noise, light, and vibrations, and cumulative impacts [2,11–15].

To facilitate comparison, each resource type and region was coded and assigned a label based on the amount of scientific knowledge available for each category:

- Scientific knowledge enables evidence-based management

- Few gaps in scientific knowledge for evidence-based management remain
- Scientific knowledge gaps for evidence-based management dominate
- There is no or next to no scientific knowledge to enable evidence-based management

These categories were qualitatively determined based upon our expert understanding of the amount of science needed to reasonably characterize pelagic and benthic communities and inform indicators and thresholds that will be used to assess and monitor environmental impacts from seabed mining.

2.2. Stakeholder consultation

A spectrum of global stakeholders responded to a questionnaire delivered via virtual interviews. Participants included scientific experts, deep-seabed-mining contractors, representatives from other industries, ISA member country representatives, other policymakers, members of the Legal and Technical Commission (LTC), the ISA Secretariat, and representatives of civil society organizations (CSOs) with a demonstrated interest in seabed-mining issues. Of the 59 global experts contacted to request an interview, 42 participated, 3 declined, and 14 did not respond. Twenty-eight respondents had primarily scientific or environmental management expertise, 14 had primarily legal or other non-scientific areas of expertise, and many were multidisciplinary. Best efforts were made to ensure geographic representation (Table S1).

All participants were asked the following questions:

a) What do you see as the critical gaps in scientific knowledge that may prevent informed decisions being made about whether deep-seabed mining can proceed in an environmentally responsible manner? What data are necessary to make that decision?
b) Of the above responses, what would be your top priorities?
c) What methods can you think of for obtaining the necessary data?
d) How long might obtaining the necessary data take?
e) Do you have thoughts on who would do that and who should fund it?
f) Do you think that the ISA currently has adequate access to scientific knowledge and if yes, are they using these data appropriately?

Additionally, non-scientific experts were also asked:

g) Do you or your organization use deep-sea scientific information to guide your deliberations related to deep-seabed mining? If yes, where do you get this information?

Two respondents noted that the framing of the first question (a) might suggest a prohibition on mining and proposed reformulation.

Interviews were transcribed and responses were anonymized, organized, and consolidated by category using Microsoft Excel. The responses informed the scientific gaps assessment and are summarized below. Answers to (c), (f) and (g) can be found in Supplementary Information.

3. Results

3.1. Literature review

3.1.1. Deep-sea environmental gaps

3.1.1.1. Polymetallic nodules. Polymetallic nodules are found on abyssal plains at depths of 3000–6500 m and over a global area spanning 38 million km^2 [6,16]. Most of the mining exploration contracts for nodules have been granted in the Clarion-Clipperton Zone (CCZ), but also in the Central Indian Ocean Basin (CIOB) and West Pacific Ocean [9]. Although baseline understanding of the CCZ is relatively more advanced than in the CIOB and West Pacific for nearly every category assessed due to greater sampling (Fig. 1), the relevant literature suggests that all nodule regions require further sampling to gather enough baseline information to enable evidence-based management.

Abiotic information: Some abiotic baseline information has been collected from the CCZ, while much less has been collected for the CIOB and West Pacific (Fig. 1). Studies have shown the CCZ to be heterogenous on multiple scales and across multiple variables, including bathymetry, geological and biogeochemical conditions, polymetallic-nodule size and density, as well as nutrient flux (including nitrogen and carbon) [17–20]. These variables may influence nodule-region communities and ecosystem functions, thus, knowledge of environmental variables is necessary for selection of proxies that can be used to inform management [19]. Important in-situ studies of microbially mediated biogeochemical processes remain very scarce [21,22].

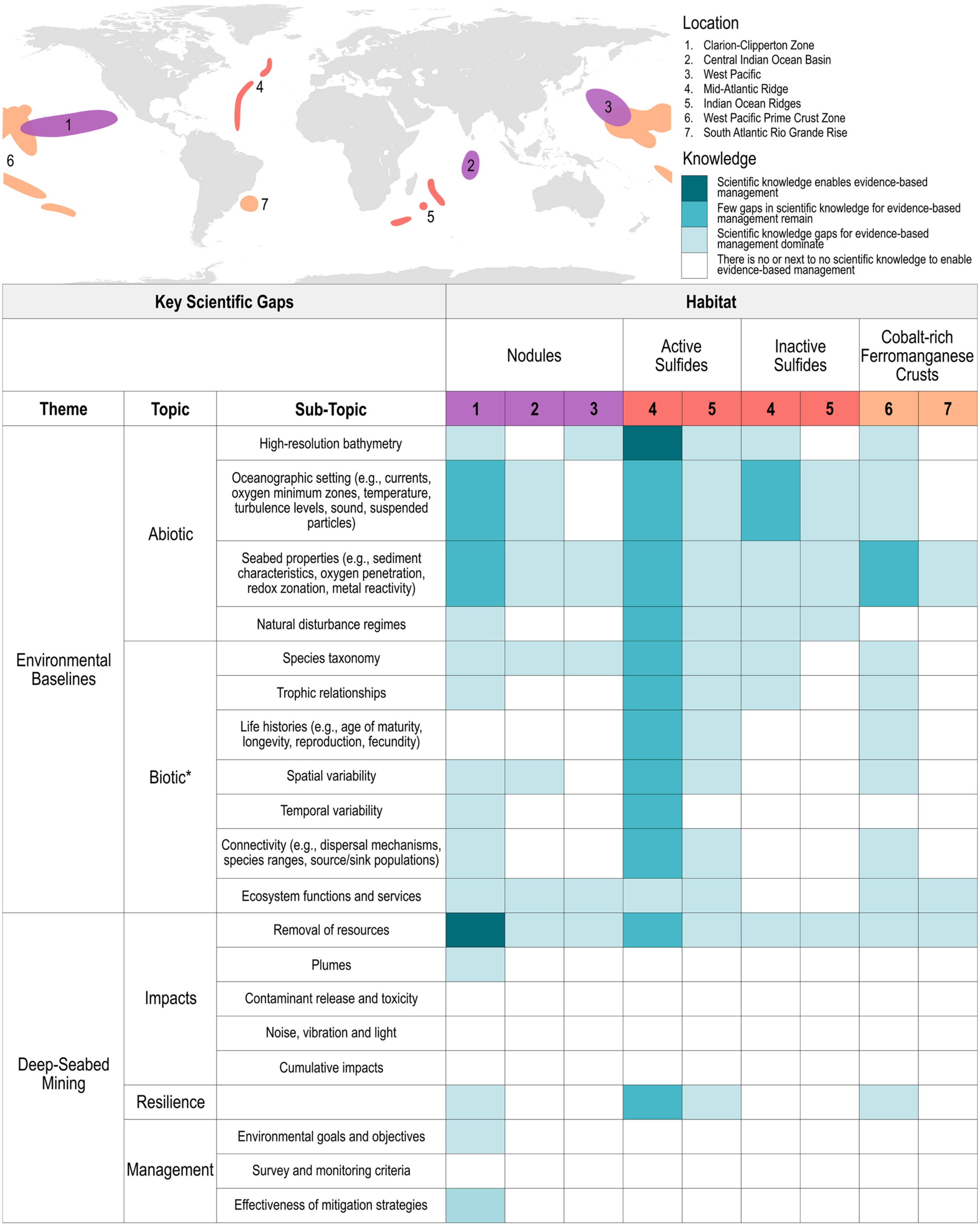
Taxonomy and ecology: Comparatively more taxonomic and ecological information is available for the CCZ than the CIOB and West Pacific (Fig. 1); however, considerable gaps remain, even in the CCZ, as approximately 70–90% of species collected from the region are new to science (and include new genera), and species-richness estimators predict a further 25–75% of total species remain to be collected at sites already sampled [23–26]. Taxonomic atlases and species descriptions produced for the region over the last decade span hundreds of taxa from multiple size classes [27–52], but more emphasis is required on sampling smaller faunal groups [23,35,53,54]. At all sizes, species collected are diverse and dominated by rarity, with most macrofaunal and meiofaunal species only collected once or twice, suggesting that the CCZ may be one of the most diverse deep-sea ecosystems in the world [15,24,25,32,33,53,55–63]. Evidence is mounting that the presence of nodules as an attachment surface may be among the drivers of biodiversity, abundance, and ecosystem function [15,33,35,53,64–67], alongside particulate organic carbon flux to the seafloor and carbon/nitrogen rations of organic matter in sediment, which serve as indicators of food availability and quality [20,22,29].

There is little taxonomic or ecological information in other nodule-rich regions, including the CIOB and West Pacific, making it a challenge to assess similarities and differences between the three areas with exploration contracts [68,69] (Fig. 1). Moreover, knowledge and baseline data remain limited about the pelagic ecosystems above these regions, particularly from depths of 1000 m to just above the seafloor, despite expectations of deep-seabed mining impacts extending to the water column [4,8,70] (Fig. 1).

Variability: An understanding of natural spatial and temporal trends would help to distinguish deep-sea mining impacts from background variability. Variability is also important for assessing resilience, prioritizing protections, and characterizing serious harm. Yet such understanding remains elusive. Data on variability has largely been haphazardly collected and not synthesized regionally [7] (Fig. 1), which suggests that concerted sampling may be needed.

In the CCZ, the benthic community structure is heterogenous and appears to be influenced by local bathymetry, nodule sizes and densities, and productivity (POC flux), but further studies are needed to confirm the nature of these relationships [15,20,24,25,49,53,55,59,62,66,71–75]. Many CCZ species appear to only occur within ranges up to 200 kilometers, which may make them more vulnerable to threats, especially given the size and scale of impacts from a single nodule mining operation [25,26,76]. In the CIOB, only one study (on nematodes) has been published in the last decade on the benthic community structure [69]. There has been no peer-reviewed research published on spatial variation within the nodule fields of the West Pacific.

The drivers and scales (e.g., intra-annual, inter-annual, decadal) of temporal variability in nodule regions are also poorly understood. Recent CCZ studies have reported changes to meroplankton (larvae of benthic fauna), nematode community structure, and vertical flux on timescales of weeks to months, likely associated with differences in primary production [77,78]. Meiofauna appear to have limited



Location

1. Clarion-Clipperton Zone
2. Central Indian Ocean Basin
3. West Pacific
4. Mid-Atlantic Ridge
5. Indian Ocean Ridges
6. West Pacific Prime Crust Zone
7. South Atlantic Rio Grande Rise

Knowledge

- ■ Scientific knowledge enables evidence-based management
- ▓ Few gaps in scientific knowledge for evidence-based management remain
- ░ Scientific knowledge gaps for evidence-based management dominate
- □ There is no or next to no scientific knowledge to enable evidence-based management

Key Scientific Gaps			**Habitat**								
			Nodules			Active Sulfides		Inactive Sulfides		Cobalt-rich Ferromanganese Crusts	
Theme	**Topic**	**Sub-Topic**	**1**	**2**	**3**	**4**	**5**	**4**	**5**	**6**	**7**
Environmental Baselines	Abiotic	High-resolution bathymetry	░	□	░	■	░	░	□	░	□
		Oceanographic setting (e.g., currents, oxygen minimum zones, temperature, turbulence levels, sound, suspended particles)	▓	░	□	▓	░	▓	░	░	□
		Seabed properties (e.g., sediment characteristics, oxygen penetration, redox zonation, metal reactivity)	▓	░	░	▓	░	░	░	▓	░
		Natural disturbance regimes	░	□	□	▓	░	░	░	□	□
	Biotic*	Species taxonomy	░	░	░	▓	░	░	□	░	□
		Trophic relationships	░	□	□	▓	░	░	□	░	□
		Life histories (e.g., age of maturity, longevity, reproduction, fecundity)	□	□	□	▓	░	□	□	░	□
		Spatial variability	░	░	□	▓	░	□	□	░	□
		Temporal variability	░	□	□	▓	□	□	□	□	□
		Connectivity (e.g., dispersal mechanisms, species ranges, source/sink populations)	░	□	□	▓	░	□	□	░	□
		Ecosystem functions and services	░	░	░	░	░	□	□	░	░
Deep-Seabed Mining	Impacts	Removal of resources	■	░	░	▓	░	░	░	░	░
		Plumes	░	□	□	□	□	□	□	□	□
		Contaminant release and toxicity	□	□	□	□	□	□	□	□	□
		Noise, vibration and light	□	□	□	□	□	□	□	□	□
		Cumulative impacts	□	□	□	□	□	□	□	□	□
	Resilience		░	□	□	▓	░	□	□	░	□
	Management	Environmental goals and objectives	░	□	□	□	□	□	□	□	□
		Survey and monitoring criteria	□	□	□	□	□	□	□	□	□
		Effectiveness of mitigation strategies	░	□	□	□	□	□	□	□	□

Fig. 1. Current level of scientific knowledge in relation to evidence-based environmental management of deep-seabed mining in regions where exploration contracts have been granted by the ISA. This has been compiled from a synthesis of the peer-reviewed literature and expert opinion, and includes both target and non-target areas within each region. * denotes benthic and pelagic habitats.

intra-annual variability in composition, standing stock, and diversity within single contract areas in the CCZ [79]. Additionally, Aleynik, Inall, Dale and Vink [17] show passing mesoscale eddies can increase abyssal currents, although not above critical erosion velocities of sediment at the abyssal seafloor, and bottom waters still have the lowest suspended particle concentrations of the ocean [19,80]. Future studies should attempt to document temporal variability across all environmental variables and biotic size classes at seasonal and interannual scales in the CCZ to more accurately characterize the ecosystem [25] (Fig. 1). This research is also needed for the CIOB and West Pacific (Fig. 1).

Connectivity: Ecological connectivity, the exchange of individuals among and between populations, influences the potentials for extinction, recovery, and recolonization of deep-ocean marine life [79,81,82]. For some benthic species, such as corals, connectivity is achieved by a planktonic larval stage, and larval dispersal is regulated by complex interactions between biotic and abiotic oceanographic processes [83]. Other species, including deep-sea nematodes, amphipods, isopods, tanaids and some polychaetes lack planktonic larvae, decreasing their ability to withstand local extinctions from disturbances. Because larval dispersal is difficult to measure directly, with high species rarity limiting robust genetic analyses, and molecular tools currently providing limited resolution [77,84,85] (Fig. 1), connectivity patterns remain poorly understood, even where they have been investigated. A recent study in the CCZ has shown that larval abundances are spatially patchy and ~1–2 orders of magnitude lower than observed at deep-sea ridge and hydrothermal-vent habitats, with a diverse assemblage of meroplankton accumulated or retained in the Benthic Boundary Layer, which could be compromised by mining plumes [77,84].

It is unlikely that connectivity patterns will be determined for all fauna, therefore, determining which species are the most functionally important could help to narrow the list. However, this should be approached with caution as larval dispersal strategies will vary among species, and species are rare at any site, with rare species likely to be functionally important as a group given how much of the abundance they constitute in aggregate [86]. In addition, rarity is often correlated with small species ranges and enhanced extinction risks [87].

Ecosystem functions and services: Functional redundancies help an ecosystem to remain resilient under stress [88]. Thus, informed decision-making will also require an understanding of how the structure and biodiversity of deep-sea marine habitats relates to their basic functions [89,90] and how these translate into important regulating, provisioning and cultural services [89–91]. These include information on bioturbation, organic matter remineralization, nutrient cycling, habitat provisioning, maintenance of population connectivity, benthic-pelagic coupling, regulation of food webs, provision of nurseries, and buffering of environmental disturbances [44,54,90,92–96], as well as the role of microbial life in these processes [88,90] (Fig. 1).

Thus far, polymetallic nodules are known to provide at least two provisioning services: a non-renewable source of minerals, and habitat to deep-sea biodiversity. Nodules provide a distinct habitat for megafauna [15,53], macrofauna [31,35,85], meiofauna [97], foraminifera [98], and microbes, with the structure and likely function of microbial assemblages in nodules being fundamentally different than in surrounding sediments [44,49,99]. The fauna in nodule regions play a role in in-situ carbon fixation, cycling and storage, although the mechanics are not well understood [88,100–102]; contribute to nutrient regeneration, which impacts fisheries at the sea surface; and could provide marine genetic resources (e.g., pharmaceuticals and biomaterials) [89]. Cultural services from nodule regions include educational and scientific research opportunities, as well as the intrinsic value of resource stewardship for current and future generations [88–91]. Questions remain as to the appropriate methodologies for measuring and valuing ecosystem functions and services in nodule regions [103], yet these regions are likely to host novel and important ecosystem processes, pathways, and mechanisms (e.g., provisioning of evolutionary potential owing to unique biodiversity).

3.1.1.2. Polymetallic sulfides. Polymetallic-sulfide deposits are produced at active vents and are retained at inactive or extinct vents after hydrothermal activity ceases temporarily or permanently, respectively. Most vents and associated deposits can be found near mid-ocean ridges and back-arc basins at depths from 1000 m to 4000 m [5,104,105]. Areas of potential polymetallic-sulfide deposits are estimated to cover 3.2 million km^2 globally, with 58% of the known sulfides in ABNJ [5,6,16,106]. It can be difficult to delimit activity status of vents, as conclusions of inactivity can be premature [107–109]. For more detailed descriptions of sulfide classification and indicators, please see Jamieson and Gartman [107] and Van Dover [109]. Mining exploration contracts targeting sulfides in ABNJ have been granted in the Atlantic and Indian Oceans [9]. Mining operations may target active, inactive, or extinct vent fields [109–111], but, as described below, mining will most likely target inactive vents [107].

3.1.1.2. .1. Hydrothermally active polymetallic sulfides. Scientific research has focused on active vents, in part because of their unique ecological processes and associated chemosynthetic taxa, which have distinguished these ecosystems as rare and vulnerable [112,113]. Over the last decade, the number of known active vent fields has doubled [114–119] and current estimates project that two thirds or more of all hydrothermal vent fields are still waiting to be discovered [120–122]. Of the regions with polymetallic-sulfide exploration mining contracts and active vent systems, the Mid-Atlantic Ridge (MAR), especially the northern section, has received the most scientific attention; however, several active vent sites approved for exploration (e.g., Pobeda) have received comparatively little study [123]. Increased sampling is still needed across the MAR to elaborate baseline categories like variability, connectivity, and ecosystem functions and services [112] (Fig. 1). Knowledge deficiency for all baseline categories is overall more severe for active vents along the Indian Ocean Ridges (IORs) [124] (Fig. 1).

Abiotic information: More studies of abiotic factors of active vents have been conducted on the MAR than on IORs [108,112,125–127] (Fig. 1). The lack of knowledge of vent ecosystems in transition areas, between active and potentially inactive regions, persists in part due to ecologists treating these ecosystems in a binary way (vent vs non-vent) rather than on a continuum [128,129]. Baseline knowledge in peripheral and background areas surrounding active vents in the Atlantic and Indian Ocean also remains poor, including the quantification of the sphere of influence of vents [70,129–132].

Taxonomy and ecology: In the last decade, a plethora of new active-vent dwelling species, genera, and families have been described [133–142]. Active hydrothermal vents exhibit high biomass of a few dominant species, species rarity (many species comprise < 5% of total abundance in samples), and high endemism, with about 70% of mega- and macrofaunal species endemic to vents and/or symbiotrophic [113,124,143]. Detailed ecological information (i.e., on trophic relationships and life histories) has been collected for a few charismatic species, including the identification of foundation species that play a crucial role in structuring and maintaining communities and novel symbiotic relationships [113,130,144–156]. However, most species inhabiting active vents, especially those of small size classes, remain poorly understood (Fig. 1). There are knowledge gaps regarding which deep-sea species rely on vent fluid and chemosynthesis for nutrition or other functions.

Variability: Hydrothermal vent communities differ between ocean basins, within ocean basins, and even on much smaller scales (e.g., within a site), with distinct zones developing as a function of distance from vent emissions [104,124,157–160]. For example, active vent communities include assemblages that are tubeworm-dominated in the East Pacific, snail and barnacle-dominated in the West Pacific and Indian Oceans, mussel and shrimp-dominated in the Atlantic Ocean, and crab-dominated in the Southern Ocean [113]. Diversity levels have also been shown to vary by biogeographic province, but sometimes can be inordinately impacted by anomalous vents [116,124]. Thaler and Amon [124] showed that the biogeographic provinces with the highest estimated biodiversity lie in the southern hemisphere, despite having some of the lowest baseline information available (e.g., on the IORs). A recent scientific review of active vent fields along the northern MAR has shown that each vent field is unique, showing distinct geophysical and biological attributes [112].

More extensive sampling will be needed to understand temporal variability at active vents [129,160–165] (Fig. 1). Some active-vent communities, typically on fast-spreading centers (e.g., in the East Pacific Rise and on the Juan de Fuca Ridge) are subjected to natural background disturbance regimes and therefore are ephemeral on decadal scales [166]. On the other hand, communities at active vents on intermediate, slow, and ultra-slow spreading ridges have habitats that persist over millennial scales (e.g., ages from the Longqi Field suggests that it has been hydrothermally active for at least ~100,000 yrs) [7,12,109,113,126,165,167] and as such, regional generalizations in temporal variability should be avoided [12].

Connectivity: At active vents, connectivity resulting from deep-ocean circulations influence faunal gene flow, diversity, and distributions [83,168,169] (Fig. 1). Active vents are ephemeral and discrete, with average spacing between vents estimated to be between 3.3 and 87 km along single ridges [120,121]. Active vent fauna show a range of dispersal techniques and degrees of connectivity [170–174]. While some species can be widespread within a biogeographic province, others are less so. For example, the Scaly-foot Snail (*Chrysomallon squamiferum*) is known from a total area less than 0.02 km^2 over three active sites in the Indian Ocean (two of which are under mining exploration contracts). This scarcity would make such species more vulnerable to the potential impacts and effects of deep-seabed mining [175,176].

Despite recent studies on connectivity at active vents, including on the MAR and IORs [116,119,136,141,170,177–185], there are still a number of obstacles and limitations to understanding these processes fully [83,186] (Fig. 1). Coupled biophysical models incorporating ocean circulation and biological traits, such as planktonic larval duration, have been used to estimate population connectivity in coastal and shallow waters. However, knowledge gaps in the physical and biological components of the vent ecosystems (e.g., mesoscale ocean physics, high-resolution bathymetry, vertical velocity, the spatial distribution of habitat types, reproductive efforts of species, planktonic larval duration, larval behavior, the identification of source populations), even for the more studied active vents of the MAR, prevent accurate modeling. The fate of larvae and mining plumes will only be approximated if detailed physical measurements (horizontal and vertical currents and eddies, overflow from mid-ocean axial valley, mixing, etc.) are made in the vicinity of the mine sites and the region [83,125] (Fig. 1). Additionally, species that do not disperse via larvae, including directly-developing macrofaunal or meiofaunal species, require further study [128]. Moreover, faunal connections between active hydrothermal vents and other chemosynthetic habitats requires further understanding as these may play a role preventing population extirpations and species extinctions, serving as a larval source, sink, or refugia [187,188].

Ecosystem functions and services: From a scientific perspective, active hydrothermal vents are unique ecosystems and meet multiple criteria for vulnerability, sensitivity, and ecological or biological significance, and classify as vulnerable marine ecosystems in need of protection [112,113]. Active vents may provide a source of minerals, but also provide substrate and shelter to deep-sea biodiversity, which can translate into provisioning services (e.g., pharmaceuticals and biomaterials), as well as regulating services (e.g., the global cycling of carbon, minerals and nutrients, contributions to surface primary productivity) [88,89,113,189–191]. Cultural services include educational and scientific research opportunities, and artistic inspiration. Active vents also have intrinsic value as resources for future generations [88–91]. There is little quantitative data for ecosystem functions and services at active and inactive vents on the MAR, and even less for the IORs (Fig. 1).

Ecosystem services from deep-sea resources are rarely incorporated into an environmental impact assessment, although Batker and Schmidt [192] provide a rare example of such an attempt, concluding that deep-seabed mining at Solwara I hydrothermal vents in Papua New Guinea was less impactful on services than impacts from terrestrial mines. This study was criticized for (1) utilizing terrestrial mining metrics, many of which were either irrelevant or failed to capture deep-sea values, and (2) reflecting inconsistencies [89].

3.1.1.2.2. Hydrothermally inactive and extinct polymetallic sulfides. In this section, inactive and extinct vents will be referred to as inactive polymetallic sulfides. Inactive polymetallic sulfides are the sulfide deposits most likely to be mined [193]. This is because 1) mining an active vent is technologically more challenging, with high temperatures (350 °C) and acidic fluids present, 2) inactive polymetallic-sulfides are suggested to be more abundant and larger than active polymetallic-sulfides deposits, and 3) there have been increasing calls for the global protection of active vents [113,193,194]. Despite the possibility of being the first polymetallic-sulfide deposit mined, there have been few published studies characterizing inactive polymetallic sulfide ecosystems, with most studies reporting anecdotal evidence [109]. As such, inactive polymetallic sulfides have one of the highest knowledge deficiencies of any of the deep-seabed mining resources for environmental baseline categories (Fig. 1). The paucity of information for inactive polymetallic sulfides is not only because research emphasis has been focused on active vents and their unique characteristics, but also because inactive polymetallic sulfides are difficult to find. Inactive polymetallic sulfides do not emit a hydrothermal plume and associated chemical signals, which are the primary means for discovering new vents [107]. Jamieson and Gartman [107] showed that of the 707 known vents listed in *Interridge Vents Database* [122], a public database hosting a global inventory of hydrothermal vents, only 20 are inactive/extinct vents.

Abiotic information: With limited quantitative studies, more studies are needed for all abiotic parameters at inactive sulfides and surrounding deep-sea habitats that may be impacted by mining (Fig. 1). Future abiotic baseline studies should focus on collecting information that will improve our understanding of the environmental impacts posing risks to these environments: overburden removal, reactivation of inactive polymetallic-sulfide deposits, seabed modification and altered hydrographic regimes, and metal toxicity. This will require a better understanding of the geological connectivity within a vent field, physical and chemical characteristics of sediments overlaying polymetallic-sulfide deposits, and background oceanographic conditions and metal concentrations [107].

Taxonomy and ecology: Inactive polymetallic sulfides have been shown to include highly diverse microbial communities, and sometimes remnant vent fauna and suspension feeders (e.g., corals and sponges), that can be as species- and biomass-rich (or richer) as active vents [12,109,195–198]. Studies have shown, unsurprisingly, that inactive polymetallic sulfides lack dense populations of chemosynthetic species characteristic of active vent ecosystems [109]. Macrofauna appear to be scarce and most of the biota do not appear to be endemic to or dependent on the inactive sulfides, showing some overlap of macrofauna and nematode species from active vents [109,199]. However, there is some evidence to the contrary [109,142]. Additionally, studies have shown that inactive and extinct vents support distinctive assemblages of megafauna found nowhere else [196,200]. Between inactive and extinct vents, there is no evidence of differences in species assemblages, though it is expected that there are differences in species associated with buried or exposed sulfides. Overall, limited anecdotal evidence and quantitative data have left questions of taxonomic identities, life histories, trophic interactions, and endemicity of all size classes of organisms at inactive and extinct vents, as well as in the water column above and communities living within the soft sediment (infauna), largely unanswered. This makes it difficult to make any generalizations about these habitats [70,109,132] (Fig. 1).

Variability, connectivity, and ecosystem services: For inactive vents, extinct vents, peripheral areas, and the pelagic zone of the MAR and

IORs, again, there is such a paucity of quantitative data that discerning patterns of spatial and temporal variation or connectivity, are not yet possible [12,109] (Fig. 1). In addition, our scientific understanding of ecological processes and characteristics, and related function and services, of inactive and extinct vents is extremely limited, hindering robust analyses of cost-benefit and risk assessments of mining in these ecosystems [201].

3.1.1.3. Cobalt-rich ferromanganese crusts. Cobalt-rich ferromanganese crusts with sufficient mineral content to be of interest to commercial mining occur between 800 and 2500 m on seamounts and occupy 1.7 million km^2 with 46% of known crusts found in ABNJ [6,16,106,202]. Exploration contracts have been granted by the ISA in the South Atlantic and West Pacific Oceans [9,203]. These are the least explored of all three habitat types targeted for mining, with only 0.4–4% (or 200–300 globally) of total large seamounts ($>$ 1000 m in height) directly sampled for scientific purposes globally [204,205]. For cobalt-rich seamounts in targeted regions, baseline conditions are not yet even partially characterized (Fig. 1).

Abiotic information: Like terrestrial mountains, cobalt-rich seamounts come in a range of shapes and sizes – from isolated, steep deep-sea features with extensive summits to clustered peaks along mid-ocean ridges – making many generalizations inappropriate [204]. Irregular topography associated with seamounts results in complex ocean circulation patterns with the potential for high spatial and temporal variability, but much more research is needed to define these patterns throughout seamount ranges (Fig. 1) [206]. Additionally, seamounts' distinct geomagnetic signatures serve as key landmarks for migratory species using these geomagnetic fields for navigation [207]. Knowing the distinct geomagnetic signatures of the seamounts is an important aspect to infer the importance of that specific location for the navigation of large marine animals. The above suggests that each seamount should be treated as a single ecological unit, discrete from other seamounts. More comprehensive bathymetric mapping and data collection of water-column characteristics are also needed to describe seamount characteristics (Fig. 1).

Taxonomy and ecology: Seamounts (like active vents) often support productive hotspots of biodiversity and are considered vulnerable marine ecosystems (VMEs) subject to special protection from fishing activities [205,208,209]. These habitats can be home to dense assemblages of sessile suspension feeders (e.g., corals and sponges) that act as foundation species supporting a wide variety of associated fauna (e.g., crustaceans, echinoderms, molluscs, and commercially important fish) [210–214], including some species that are very large and long lived [211,215,216]. Most of the seamounts and ridges in the South Atlantic and West Pacific have not been taxonomically or ecologically characterized [7,211,215–228] (Fig. 1). Uncertainty remains regarding differences between fauna associated with crusts and similar non-crust areas, the rarity of inhabiting species, what pelagic fauna are present, and whether chemical components of the crusts are dominant drivers of benthic assemblage [212,227].

Variability: There is growing evidence that seamounts, including potential mining targets, are highly heterogeneous habitats given each seamount's diversity of megafaunal communities, varying topography, and oceanographic environments [195,212,225,227]. Many of these parameters vary significantly over small temporal scales. For example, Taylor columns that enhance productivity and upwelling may only occur at certain unpredictable times of year. Little is known of the temporal variability of cobalt-rich seamount ecosystems in the West Pacific and South Atlantic Oceans, however, there has been at least one study on framework-building corals elsewhere that show strong variability in growth rates (up to 4 cm per year) linked to hydrographic conditions [229]. Because these parameters can also vary greatly from spatial scales of $<$ 15 cm within regions, to $>$ 10 km between regions [205,227,230], managing seamounts will require extensive community spatial analysis [225].

Connectivity: Connectivity among seamount populations reveals contrasting patterns among species: some seamount species are distributed across large geographic distances, but several studies highlight high uniqueness in seamount fauna [231–233]. This could be due to ecological and evolutionary processes or may be linked to the low sampling effort and paucity of genetic studies on seamount species [12,222,234]. The relevant literature suggests a need for increased sampling at spatial scales greater than those of the mining contracts in both the West Pacific and South Atlantic to enable effective management (Fig. 1).

Ecosystem functions and services: There is little to no quantitative data for most ecosystem functions and services for the seamounts in the deep West Pacific and South Atlantic [230] (Fig. 1). Ferromanganese-encrusted seamounts have been shown to support biodiversity and play a role in biological enrichment, increasing ocean productivity, and carbon sequestration [88,235,236]. Provisioning services, especially fisheries, but also pharmaceuticals, biomaterials, and potential non-renewable minerals, are also supplied [89,208,235]. Cultural services include educational and scientific research opportunities, as well as intrinsic stewardship values [88–90]. Questions remain as to how ecosystem structure links to function, how these functions and services should be measured and valued, which species are most significant, and the potential for novel process and pathways [14].

3.1.2. Scientific gaps of the impacts of seabed mining

3.1.2.1. Environmental impacts of deep-seabed mining. Serious concerns have been raised over the potential environmental impacts related to deep-seabed mining if it commences, especially given the vast number of unknowns about the relevant habitats [5,110]. In lieu of actual tests at commercial scale, some knowledge has been gleaned from small-scale, low-intensity experiments in nodule regions only [237]. Peer-reviewed studies of small-scale mining tests that include details of environmental assessment do not exist for sulfides or crusts, and thus most of the potential impacts and effects have been extrapolated from other extractive activities such as fishing, and natural events. Due to limited or no data across all three resources, the impacts and associated effects of deep-seabed mining have not been directly evaluated (Fig. 1), although ecosystem characteristics provide important insights into likely sensitivities to mining disturbance [7].

Small-scale tests of mining devices and proposals for full-scale commercial operations have suggested what commercial mining operations will look like for each resource [110,237–240]. Publicly-available concept designs show collector vehicles with caterpillar treads to recover the nodules from the top 1–20 cm of surface sediments through mechanical means or hydraulic jets [110,237]. The collecting devices will be connected to a pump and riser system to lift nodules to the surface [110,237]. Movements of the large collecting device (e.g., at 1–2 knots over the seafloor) plus separation of nodules from sediments at the seafloor will create suspended sediment plumes in bottom waters. Entrained water and fine particles lifted to the ship will be reinjected into the water column (depth still to be determined, but ideally at the seabed) through a dewatering pump and pipe. Mining of polymetallic sulfides and cobalt-rich ferromanganese crusts are likely to both employ three machines to extract the deposits: 1) a cutting machine to flatten the topography and create benches, 2) another cutting machine to further disaggregate the benches, and 3) a collecting machine which will suck the disaggregated rock through a pump and riser system as a slurry [110].

Based on the above mining techniques, it is generally expected that all three types of mining will produce environmental impacts in five categories: (1) removal of the resources together with the biologically active benthic zone, i.e. fauna and seafloor surface; (2) generation of sediment plumes created from the disturbance on the seafloor ("collector plume") as well as from the return water ("dewatering plume") that may cloud the water column or smother/blanket unmined seafloor areas; (3) chemical release (including metals) and changes to water properties; (4) increases in noise, vibration, and light; and (5) cumulative impacts [2,11–15]. The resulting environmental effects may include loss of seafloor integrity, reduced biogeochemical process rates, and biodiversity, as well as species displacement, and in turn, modified trophic interactions and loss of connectivity, which could lead to species extinctions and loss of ecosystem functions and services [4,5,11,22,85,110,111,241,242–244]. There may also be conflicts with existing activities; for example, the fishing industry could see reduced fisheries catch, displacement of fishing effort, and/or spatial concentration of fishing effort promoting depletion of background areas [245]. The potential environmental effects for each impact are discussed below in more detail.

Removal of the resources: Through small-scale studies in the CCZ, Peru Basin, and the CIOB nodule regions, there is a basic understanding of the environmental effects of resource removal (Fig. 1). It is expected that direct removal of all three resources, which act as substrate/habitat for sessile or partially sessile fauna, and removal and compaction of sediment will result in decreased habitat availability and loss of biodiversity [13,15,22,241,246]. Given our current understanding of proposed mining operations and durations, the direct impact (not including plumes) for nodule provinces is expected to be 6–15,000 km^2 per mine, at vents < 10 km^2 per mine, and at cobalt-rich crusts 10–100 km^2 per mine [7,247].

Studies in the CCZ and Peru Basin have shown that after small-scale, mining-type disturbance (nodule removal), reduced faunal biodiversity, and altered species composition and ecosystem functions remain over 2-4 decades later [15,22,237,246,248–250]. This could lead to an irreversible change, decline, or loss in key ecosystem functions such as nutrient and carbon cycling, habitat provision, maintenance of population connectivity, regulation of food webs, especially in directly disturbed areas [21,22,67,101,241,244,246,251] and lead to local extinctions of species reliant on nodules. The recovery of these ecosystems for motile sediment-dwelling fauna could take hundreds to thousands of years due to low sedimentation rates [241,244], whereas fauna that rely on the nodules may not recover for millions of years as the nodules regrow very slowly (ca. 250 mm/My) [12,35,53,61,247,250]. More research is needed to assess the impacts of resource removal in the CIOB and West Pacific, as well as the impacts on connectivity and ecosystem services in all nodule regions (Fig. 1).

At hydrothermal vents, the primary substrate used by fauna will be removed, along with the fauna itself, likely leading to species extinctions at active vents given the high endemicity of fauna at these habitats [109]. For inactive polymetallic sulfides, it is not yet known how detrimental the loss of species will be, but these changes could be permanent at inactive vent sites as the habitat will not reform [109]. There is also a concern that mining could lead to fluid flow disruptions at active vents and the reactivation of inactive vents, subsequently altering abiotic conditions and species assemblages.

For cobalt-rich ferromanganese crusts, extraction is also expected to kill fauna and remove the primary substrate [110]. Suspension feeders, such as cold-water corals and sponges, and other slow growing organisms are expected to be particularly vulnerable to the removal of substrate [5,12,215,216,227,252–255]. Isolated seamounts may also host endemic species more prone to extinction [110,204,205], but if all contracted areas in mid-ocean ridges and seamounts are to be exploited, the cumulative impacts will have an unprecedented impact on the deep-sea fauna and hence requires a holistic ocean-basin scale assessment. There have been no tests yet in ABNJ where deep-seabed mining exploration contracts exist for ferromanganese crusts, so it is difficult to discern the extent to which resource removal may affect these environments.

Plumes: Models and small-scale experiments in nodule regions suggest that plumes from mining may re-suspend sediments and cloud the water column for long periods, which could impact pelagic fauna, before eventually resettling elsewhere to impact benthic fauna [4,13,256–258]. The dewatering plume's release depth remains unknown, making it difficult to predict the distance dewatering plumes will travel vertically and horizontally, and how this will affect pelagic and benthic ecosystem within and beyond contract areas [4,70]. A recent study showed that modeling could reliably predict the properties and extent of the dewatering plume for a few hours, and within a few kilometers of the discharge [259]. It also showed that the scale of increased sediment concentrations relative to background levels from the plume is influenced by turbulent diffusivity (i.e., intensity of mixing) and the quantity of sediment discharged, with flocculation not considered a significant factor.

Currently, there are no publicly available data for mining-equipment tests limiting our understanding of the quantity of sediment discharged by a full-scale mining operation. Filling these knowledge gaps would require data on collector and riser mining technology, and information on the separation process on board the vessel. In lieu of these data, we are left with estimations based on the projected resource extraction rates. A single CCZ mining operation is estimated to directly mine 1–2 km^2 per day, discharging 30,000–80,000 m^3 of sediment, broken mineral fines, and seawater (~8 kg per m^3 solids), which could result in a seafloor disturbance 2- to 4-fold larger than a direct mining footprint due to turbidity and re-sedimentation from collector (suspended mining) plumes [4,7,11,70,104]. These discharges could produce 500,000,000 m^3 of discharge over a 30-year period for one operation [4]. For a hydrothermal-vent operation, the discharge could be 22,000–38,000 m^3 per day [4,240]. For mining of cobalt-rich crusts on seamounts, the spatial scale of collector plumes may not be as large, with a recent study showing the dispersion of sediment plumes to be significantly reduced by the effects of flocculation, background turbidity, and internal tides [258], but this may vary across seamounts.

The literature suggests that mining plumes are expected to be harmful to ecosystems at all three resources, although without a better understanding of the depth and properties of the discharge and sediment tolerances of fauna, the spatial scale of impact is unclear [247]. The suspended sediments from plumes may smother organisms (clogging respiratory surfaces) or impair the feeding organs of suspension feeders making up a large portion of the benthic fauna [33,35]. This may be especially harmful in nodule provinces as these are dominated by low-sedimentation regimes, with very clear bottom waters [80], are host to many associated adapted (therefore sensitive) fauna, and would further be subjected to gravity flows caused by the disturbance and suspension of the upper 10+ cm of the sediment [16,104,257]. Deposition from plumes will also dilute the food for deposit feeders that dominate abyssal sediment communities and could also change the seabed morphology, availability of labile organic matter within the sediment, and bury and smother nodule habitats and benthic biota [13,260].

Animals living in the midwater and at the seafloor in nodule regions are likely to be particularly sensitive to plumes given the low concentrations of naturally suspended sediments. Increased sediment concentration could result in clogged gills, impaired feeding, a reduced ability to communicate, and effects from increased toxicity [4,13]. This could ultimately result in significant changes in entire ecosystems and the services they support, including commercially exploited fish species [4,13,70,74,84,94,208,261]. However, we do not have any empirical data on suspended sediment sensitivities for animals below ~200 m upon which to generate evidence-based response thresholds.

Contaminant release and toxicity: The release of chemical substances, including metals, will likely impact water properties at all three mining target environments [13,262]; however, mining of sulfide deposits is expected to have the greatest potential for metal toxicity, due to the high oxidation potential of sulfide minerals, with potential for sublethal and lethal effects on ingestion by pelagic and benthic organisms [262,263]. Assessing toxicity and its effects in deep-sea species is technologically challenging, so the responses of deep-sea fauna to toxins are still poorly known for all three resources [262,264] (Fig. 1). However, higher metals concentrations in the water column are expected to have environmental effects, such as reducing levels of available oxygen in the environment, and bioaccumulation in commercially important fish species [4,110]. Other industries can shed light on toxic effects [265–267]; however, comparisons should be approached with caution, as the effects of temperature and hydrostatic pressure on toxicity are not well understood [262,264].

Noise, vibration, and light: Deep-seabed mining will increase noise, vibration, and light in an already polluted soundscape [4,5,13,268]. Thus far, little is known about the potential impacts of noise (particularly in the Sound Fixing and Ranging (SOFAR) channel), vibration, and light (e.g., in the deep-scattering layer) from the mesopelagic to the subseafloor, due to a lack of publicly-available baseline knowledge and quantitative information on the specific mining technology [4] (Fig. 1). Lin, Chen, Watanabe, Kawagucci, Yamamoto and Akamatsu [269] have hypothesized that sound may act as a settlement cue in specific habitats in the deep sea as it does on shallow-water coral reefs. If so, noise from shipping, drilling, and mineral-retrieval machinery, as well as discarding of cuttings, during the mining process could mask the natural deep-sea soundscape and affect marine mammals and other species in and around the mining areas [12,268–271].

Cumulative impacts: There have been conceptual attempts to qualitatively model cumulative impacts [272]. Current quantitative analyses are only considering the mining impacts in individual contract areas (e.g., by running models) but are not considering potential additive impacts of multiple mining operations across the region. This includes not only the sum of different sources of mining impacts but also the sum of similar impacts on larger spatial scales. Other non-mining anthropogenic impacts could also interact additively or synergistically with mining activities, altering biodiversity and associated ecosystem functions [7,273–275]. A systematic accounting of existing non-mining anthropogenic impacts, including from fishing (especially on seamounts) [253,255,276], pollution, and climate change [273,277,278], is needed to understand these interactions in all three resource environments (Fig. 1).

3.1.2.2. Resilience to deep-seabed mining.

Understanding resilience, defined here as the ability of a system to maintain its overall function and structure (through resistance or recovery) in light of internal or external stress, is contingent upon obtaining robust baseline information on ecosystem structure and dynamics (densities, biodiversity, life history, growth/maturation rates, longevity, colonization potential, distributions, dispersal modes, larval sources and sinks), an understanding of individual mining impacts and cumulative impacts, and tolerance thresholds and tipping points to changing conditions [12]. Resistance to harm altogether is unlikely to be achievable, particularly at the mine site; thus, the potential for recolonization or recovery are critical [5,111,242]. Information on faunal and ecosystem resilience is limited for all three resources [48,79] (Fig. 1).

Based on available information in relation to mining methods and tools, resilience in nodule regions is expected to be low, with recovery of sediment fauna and functions requiring many decades, and nodules requiring millions of years to regrow the habitat structure, following disruption of their habitat [18,21,237,241,247,251]. Furthermore, the generation of sediment plumes during the mining process could potentially slow recovery as bentho-pelagic larvae, necessary for repopulation, may be disproportionately affected [77]. Additionally, Haffert, Haeckel, de Stigter and Janssen [241] showed that the recovery of the abyssal sediment community in the Peru Basin depends on an intact upper-reactive sediment layer, where microbial degradation of the available reactive organic-matter fraction helps to sustain larger animals able to undertake bioturbation and speed up the recovery process; regeneration of this sediment layer via the low natural deposition could take thousands of years.

At hydrothermal vents, distinct global faunal patterns, vent site distances, and natural background disturbance regimes make it difficult to generalize resilience to mining disturbances for these ecosystems [5,12,124] (Fig. 1). For example, mine disturbance simulations on active vent communities estimated recovery of Northwest Pacific vents to range from 20 to 100 years, whereas recovery times in the Southwest Pacific were much shorter, with some active vents predicted to recover within five years [243]. Additionally, back-arc basin vents and their communities experience slower natural changes and a lower frequency of natural disturbance than mid-ocean ridge systems with similar spreading rates, which may make them less resilient to anthropogenic disturbances [167]. Additionally, loss of foundation species and alterations to sulfide fluid-flow pathways could prevent recovery [109].

For inactive polymetallic sulfides, there is little baseline information to assess ecosystem resilience [5,12] (Fig. 1). It is anticipated that recovery of sessile invertebrate taxa will depend on larval recruitment, which may be site and species specific, and also depend on exposed hard substrata and degree of taxa endemicity [109]. There has been no study of likely resilience and recovery rates of encrusted seamounts from mining, but analogies may be drawn from sparse megafauna data from bottom trawling [12]. These studies have shown that the recovery of megafauna dependent on polymetallic crusts on seamounts will likely require thousands to millions of years, given the rate of the formation of crusts (1–5 mm per million years) as well as of growth of coral (depending on the taxa and what substrate was left) [5,12,211,227,247,279]. It should also be noted that time or potential for recovery of fauna and functions may not be equal on all seamounts. Data on recovery rates of associated meio- and macrofauna after trawling do not exist [5].

3.1.2.3. Management of deep-seabed mining.

Environmental goals and objectives: Defined strategic environmental goals and objectives are the starting point for assessing environmental responsibilities [280]. These strategic environmental goals and objectives should be overarching, uniformly applicable to all deep-seabed mining in ABNJ, and guide all decision-making, including the identification of scientific knowledge gaps and the approach to resolving them [280]. Strategic environmental goals and objectives will also be critical for the establishment of regional environmental goals and objectives to accommodate the different resources and their ecosystems. Both types of environmental goals and objectives are necessary to prevent serious harm, a term that has yet to be adequately defined in the context of the deep ocean [2,280]. For example, clear decisions about what questions need to be answered to achieve the environmental goals and objectives will guide what should be sampled and in what order and timeframe. Examples of environmental objectives include the protection of regional biodiversity, community structure, ecosystem functions and ecosystem integrity, and/or the management of impacts to as low a level as reasonably practicable and consistent with UNCLOS requirements [280]. To date, regional environmental goals and objectives exist only for the areas of particular environmental interest (APEI) network in the CCZ as part of the Regional Environmental Management Plan (REMP); however, beyond the implementation of protected areas (see Discussion below), little else has been proposed or implemented in this REMP [281] (Fig. 1).

There are a number of key concepts and principles from the Convention on the Regulation of Antarctic Mineral Resource Activities (CRAMRA) that could also be useful strategic goals and objectives to consider adopting, e.g., avoid significant adverse effects on 1) air and water quality, 2) atmospheric, terrestrial or marine environments, and 3) distribution, abundance or productivity of populations of species [282]. However, to move this forward, humankind needs to come to a consensus on how to operationalize these environmental obligations.

Survey and monitoring criteria: Survey and monitoring criteria will be essential to ensure that targets used to evaluate whether the regional environmental goals and objectives are being achieved and enable contractors and regulators to intervene before mining activities cause serious harm. These monitoring design and criteria will be most effective if they reflect these targets along with trigger points and ecological thresholds, which will need to be set by regulators following a more robust understanding of the deep-sea environmental baseline [2,5].

A trigger point may fall at the extremes of natural variability and will indicate that an ecological threshold, the point at which changes exceed natural variability and may lead to serious harm, is being approached, with mitigating action required as soon as possible to prevent non-compliance [2]. Currently, trigger points and thresholds to guide monitoring efforts are rarely or poorly delimited given the insufficient baseline information available (Fig. 1). By comparison, available baseline data from shallow-water ecosystems for various environmental parameters are much more comprehensive than the deep sea [7]. Applying a precautionary approach in these circumstances should lead to heightened restrictions and conservative values being set until several threshold indicators are better characterized [2,283].

Potential examples of abiotic indicators include sediment and water-column metal toxicity, oxygen and suspended-sediments levels, and rates of sedimentation on the benthos [2]. Key biotic metrics at the population level could include measures of abundance, biomass, habitat quality, population connectivity, and reduction below critical reproductive density [2]. Community-and ecosystem-level indicators include biodiversity (alpha-, beta-, and gamma diversity), shifts in community assemblages, decline in foundation species and/or other dominant species, alteration of key trophic linkages among species, biomass production, and disturbances in oxygen consumption, carbon remineralization, and nutrient recycling [2]. Identification and understanding of indicator species or surrogate species (e.g., of functional importance, that are fragile, vulnerable, or have a high extinction risk) will be a key component for establishing triggers and thresholds [2]. However, ecological information is so limited in many areas targeted for mining (e.g., the CCZ) that identification of indicator species, especially for chronic disturbance (e.g., exposure to sediment plumes for months to years) is currently not possible. This may be further complicated by the high diversity and rarity of species [25].

Given the low densities and prevalence of singletons, doubletons and tripletons in the communities, ensuring there is not only enough taxonomic resolution, but also enough statistical power, should also be a standard component of deep-seabed mining planning, monitoring, and reporting, as without this, a "no effect" result could mislead and give a false sense of assurance [25,284]. For example, Ardron, Simon-Lledó, Jones and Ruhl [285] found that to detect a simulated tipping point from high-resolution photo or video transects, impact monitoring samples should each have at least 500–750 individual megafauna; and at least five such samples, with control samples also being assessed. That equates to approximately 1500–2300 m^2 seabed per impact monitoring sample, or 7500–11,500 m^2 in total for a given location and/or habitat [285]. However, detecting less severe disturbances or a similar level of disturbance in an area with naturally lower abundance of fauna may require more sampling. More of these types of studies are needed as the results will be taxon- and location-specific. Adequate physical sampling of the more diverse macrofauna is even more challenging (e.g., Jumars [286]).

Mitigation strategies: Despite calls for restorative actions in degraded habitats, there are no tested approaches to restore or rehabilitate deep-sea ecosystems (including the overlying water column) [103,111,113,287], or achieve a goal of no net loss of biodiversity [242]. Additionally, the likely high cost and technical challenges of restoration techniques may be insurmountable for the deep sea, especially over the vast spatial scales ($>$ 10,000 km^2) expected to be impacted by nodule removal [5,14,111,242]. Instead of pursuing the use of restoration techniques, it may be more advantageous for managers to seek ways to reduce impacts through protection, mining equipment innovation, and expansion of knowledge of other mitigation strategies [274,287,288]. Mitigation strategies (avoidance, minimization, rehabilitation/restoration, off-set) rely on the ability to define and measure "serious harm", as well as knowledge of the mining technologies and plans [2]. Evaluation of the potential impacts of the mining operation by undertaking EIAs is also essential so that impacts can be identified, avoided and minimized [289]. As none of these have been fully undertaken, the effectiveness of mitigation strategies based on currently disclosed mining methods in all three habitats remains inconclusive (Fig. 1).

Setting-aside protected areas at the individual mine and regional scale have been indicated as part of the ISA's spatial management strategies to both monitor and mitigate mining impacts and effects, however this is still in its infancy [20,290]. At the individual mine scale, contractors are expected, per the exploration and draft exploitation regulations, to establish impact reference zones (area expected to be impacted by deep-seabed mining) and preservation reference zones (area not susceptible to deep-seabed mining impacts) within their contract areas for the purposes of monitoring impacts [291,292]. At present, there is little guidance on the size, quantity, and representativity needed to ensure that these zones are usable for monitoring impacts, which will be needed by contractors and the ISA to develop and evaluate EIAs and EMMPs [15,290]. At the regional scale, the ISA has proposed the use of REMPs, which would, among other things, designate a series of APEIs, which would be ecologically similar to neighboring mined areas and collectively encompass the full range of habitats, biodiversity, and ecosystems functions and services within the region [25]. Designation and protection of effective APEIs from mining is an important step for preservation of regional biodiversity and ecological function, but rarely is feasible and adequate if done after exploration contracts are fixed.

Currently, the CCZ has the only APEI network [20,227,272,293]. The location and size of the APEIs for the CCZ were based largely on abiotic conditions which suggested there were nine distinct biogeographic regions in the CCZ [20,25]. More recent studies have suggested that the APEIs may not adequately capture the full range of habitats in the CCZ, especially those richest in nodules [18,55,85,294]. For example, Christodoulou, O'Hara, Hugall, Khodami, Rodrigues, Hilario, Vink and Martinez Arbizu [55] and Volz, Mogollón, Geibert, Arbizu, Koschinsky and Kasten [18] sampled a small area in APEI3 and concluded that its biogeochemical features and biological community differ considerably from some nearby contract areas, and thus may not be a good surrogate area for the CCZ nodule fauna and is ill-suited as a representative area of the recovery of the potentially mined areas. Furthermore, Taboada, Riesgo, Wiklund, Paterson, Koutsouveli, Santodomingo, Dale, Smith, Jones, Dahlgren and Glover [85] found that a small area sampled in APEI6 may be inadequate to serve as a population source for a hexactinellid sponge species. Additionally, a recent assessment of habitat representativity for the CCZ APEI network showed that several habitat classes with high nodule abundance are common in mining exploration contract areas, but currently receive little to no protection in APEIs [25,294]. These studies have prompted the need to shift or add new APEIs closer to the CCZ core area to ensure that population connectivity is retained between APEIs and mine sites, and to ensure that they consist of similar nodule abundance [15,25,55,294].

3.2. *Stakeholder consultation on scientific gaps and associated issues*

3.2.1. *Scientific gaps and priorities to inform environmental management of seabed mining*

Most respondents (88%) concurred that deep-sea scientific knowledge is currently too sparse to minimize environmental risks and ensure the protection of the marine environment in the face of large-scale, deep-seabed mining. The remaining respondents did not express an opinion on the matter (7%) or advocated that despite the high levels of uncertainty, decisions could still be made (5%). There was also caution from one respondent that closing the scientific gaps would not matter if political will and an effective decision-making framework remained unestablished. Many respondents primarily focused on polymetallic nodules, specifically the CCZ, given that this may be the first resource and region to be exploited in ABNJ.

The most cited scientific gap was comprehensive environmental baseline information for the regions where deep-seabed mining may occur (71% of respondents – 79% of non-scientific experts and 68% of scientific experts) (Table 1). Respondents stated that baseline information is needed for both the seafloor and water column within and outside contract areas across all three resources. Respondents also stressed the need to understand all size classes of fauna including microbes, small naked protists, foraminifera, and meiofauna, and especially the most vulnerable fauna: those living on the targeted resources themselves.

Understanding the impacts of deep-seabed mining was the second most raised critical scientific gap (69% of respondents – 79% of non-scientific experts and 64% of scientific experts) (Table 1). This includes the spatial and temporal extent of both direct and indirect impacts, with the former mentioned more frequently. The most referenced impact was related to the footprint extent and duration of the sediment and discharge plumes. Sediment plumes' behaviors have been modeled in the dredging industry, but more information is needed with studies on seabed mining currently being undertaken. Scientific respondents in particular, noted their concern that very little communication currently occurs between oceanographers and engineers despite this being a very powerful tool for mine-site planning. Related unanswered questions raised included:

- What will be the characteristics of the plumes including of the particulate and dissolved fractions?
- How will the plumes be impacted by the ocean currents and turbulence levels in the relevant regions?
- How will the plumes (e.g., physical and chemical parameters, ecotoxicology, particle shape) impact deep-ocean biodiversity including specific species?

Respondents also flagged how little is known about the potential impacts of noise (particularly in the SOFAR channel), vibration, and light (e.g., in the deep-scattering layer) from the sea surface to the subseafloor.

Biological response (resilience) to seabed-mining impacts was the third most cited issue (by 48% respondents) (Table 1). However, it was unclear whether some respondents distinguished "resilience and recovery likelihood" from the general gap of "impacts of deep-seabed mining".

Informed decisions should weigh any potential benefits of seabed mining against the potential loss of ecosystem functions and services. Forty-one percent of respondents raised ecosystem functions and services as a key scientific gap (Table 1). Three respondents (7%) raised the specific need to understand how oceanic and coastal fisheries might be impacted by deep-seabed mining given the reliance of a large proportion of the global population for sustenance and revenue, including in States considering seabed mining or near mining sites. Lethal effects may result in declines in catches, while sublethal impacts may reduce seafood quality. Another gap raised was an understanding of how critical the substrate-inhabiting fauna are in the functioning of these ecosystems.

Table 1
Prioritized list of scientific gaps based on feedback from respondents during the stakeholder consultation.

Rank	Critical Scientific Gap	% Respondents
1	Environmental baselines in the deep ocean	71
2	Impacts of deep-seabed mining	69
3	Resilience to deep-seabed mining	48
4	Ecosystem functions and services in the deep ocean	41
5	Survey and monitoring criteria	33
5	Connectivity in the deep ocean	33
7	Variability in the deep ocean	24
8	Cumulative impacts	21
9	Mining technologies	12
9	Effective translation of science for use by other stakeholders	12
11	Strategic environmental goals and objectives	7
11	Holistic and mine-site planning	7
11	Validity of existing scientific data	7
11	Effectiveness of mitigation measures	7
15	Use of traditional knowledge	2

The parameters used to effectively survey and monitor the impacts of deep-seabed mining on the benthos and water column have not yet been identified, thus remaining a scientific gap according to 33% of respondents (Table 1). This is likely because, as reminded by one respondent, in the realm of deep-seabed mining, the process of defining these has only been undertaken once before (at Solwara 1, Papua New Guinea).

Determining the nature and scope of an impact of human activity requires a comparison to natural variability in the deep ocean. This was also identified as a key scientific gap by 24% of respondents. Respondents also indicated identifying trends would require clear definitions of deep-sea ecological structure and function, which in turn requires an understanding of the linkages and relationships within. This impedes conclusive and holistic statements on habitat classification and the scales of impacts from an ecosystem perspective. Connectivity was understood to be a critical gap by 33% of respondents (Table 1). Respondents perceived this to be (relatively) best understood at polymetallic sulfides, then polymetallic nodules, and ferromanganese-encrusted seamounts.

Cumulative impacts are very difficult to measure, understand, and manage, and thus remain a key scientific gap according to 21% of respondents (Table 1). Some respondents anticipated impacts would increase in severity exponentially as more mining operations commence and possibly due to the impacts of climate change and other anthropogenic activities. Respondents stressed that assessment of cumulative impacts must incorporate changing climate scenarios. Respondents, particularly from Small Island Developing States, were also worried about deep-seabed mining impacts on carbon sequestration and climate change.

Several respondents (7%) commented on the large volumes of scientific environmental data relevant to deep-seabed mining that currently exist, including contractors' baseline data, that remain inaccessible, preventing the quality control, analysis, and integration into openly available databases for regional analyses (Table 1). It was also noted that contractor data needs to be comparable, using common taxonomy, methodology, and standards, to enable their use for regional analyses.

Future mining technologies and how they will operate are still under development and thus, not well known, according to 12% of respondents (Table 1). To understand the specific impacts, delineate monitoring criteria, and mitigate these impacts, this essential information is needed and should be made publicly available.

Scientific data needs to be translated into information, and finally knowledge, that is practical and communicated to fit into existing or planned processes and procedures, where it can be consumed by non-specialists. A disconnect between scientists and other stakeholder groups may result in interactions related to science being abstract, jargon-filled (e.g., ecosystem approach), and unspecific, which can sometimes lead to miscommunication and planning error. When science is not accessible to seabed-mining policymakers, the operationalization of regulation frameworks can be hindered. This was raised by 12% of respondents as an issue. Respondents also highlighted the need for translation between scientists and engineers, as well as industry.

Defined strategic environmental goals and objectives were identified by 7% of respondents as the starting point of assessing environmental responsibilities and should articulate what the result is that needs to be achieved both scientifically and from a management perspective.

Holistic (at the basin level) and mine-site planning, informed by high-quality scientific data and robust environmental understanding, is a critical gap, which, if closed, was stated by 7% of respondents to lead to better decisions and environmental outcomes without compromising mining potential. However, at least 12% of respondents flagged the issue of scientists focusing only on their area of expertise, ultimately preventing efforts from being directed to a holistic ecosystem approach.

As timescales for recolonization and recovery are generally expected to be long, respondents questioned whether it would be possible to restore affected areas and how this would be done (e.g., reseeding with synthetic nodules or bioactive organic matter). Additionally, respondents raised whether spatial-management mechanisms (e.g., APEIs, PRZs) would effectively execute their roles in the preservation of the biodiversity, functions, and services from the impacts of seabed mining.

Thus far, traditional knowledge from Indigenous Peoples and local communities has been largely ignored in decision-making processes and management-mechanism implementation, despite valuable and comprehensive understandings by these important knowledge holders. A clear process for incorporating traditional knowledge as a complement to science and as part of an overall knowledge base is needed, according to one respondent. Concern was also expressed related to culturally significant species that range between coastal waters and the high seas (e.g., eels, whale sharks and tuna), especially in the Pacific and Arctic Oceans, and how they might be affected by deep-seabed mining.

3.2.2. Suggested time to bridge scientific gaps

The length of time needed to close the critical scientific gaps related to deep-seabed mining was the most difficult question for most respondents to answer, resulting in only 20 responses (six from non-scientific experts and 14 from scientific experts) that contained a timeframe. Many acknowledged that this would be largely dependent on marshaled resources (e.g., effort and funding), which seemed more problematic due to COVID-19 and the resulting economic crises. Answers were highly variable, stretching from three years to several decades to generate critical knowledge on the environmental baseline, potential impacts, and recovery.

Of the 20 respondents that specified a timeframe, only 10% suggested a timeframe shorter than five years. One respondent stressed that regardless of funding, it was impossible to do a baseline study and EIA that captured temporal variation in under three years. In their opinion, 3–5 years was a more appropriate timeframe, but this would require maximum effort and funding. Another respondent echoed this: if assuming existing levels of baseline knowledge, then further data collection, plus component testing and 1–2 years of analysis could be achieved in under 5 years.

The remaining respondents were evenly split between periods of 6–10 years, 11–20 years, and more than 20 years. Thirty percent of respondents estimated between 6 and 10 years to close the critical scientific gaps. This would allow for lab-based experiments, field sampling in these often remote and vast areas (including the incorporation of temporal aspects such as seasonal variation), and subsequent analysis, especially if utilizing techniques such as turbo-taxonomy [295]. Thirty percent of respondents estimated a period of 11–20 years was needed to get the scientific community to a reasonable place to make evidence-based recommendations that are responsible and minimize damage. The UN Decade of Ocean Science for Sustainable Development was cited as a good opportunity to gather this critical data, especially given the overlapping emphasis on international collaboration, to engage a broad spectrum of deep-sea practitioners across multiple generations (e.g., academics, industry, philanthropy, data managers), and to use the ensuing scientific advance to address the Sustainable Development Goals [296]. This could also potentially allow for reflection on the future direction of this nascent industry, including in the context of other ocean pressures. The JPI-Oceans Mining Impact Project was mentioned as a good model to follow as it gathered both baseline and applied knowledge within a ten-year period utilizing key partnerships. However, while this timeframe would allow for the development of mining technology and component testing, Mining Impact phases 1 and 2 did not have sufficient time to study full-scale mining tests. Additionally, this JPI-Oceans project only focused on polymetallic nodules, with additional time needed for gathering scientific data for polymetallic sulfides and ferromanganese crusts.

The 30% of respondents that estimated a timeframe of longer than 20 years did so mainly because of the lack of existing temporal baseline in the deep ocean, including in targeted areas. Thus far, spatial-scale studies have primarily been the focus of deep-ocean research, resulting in poor knowledge on decadal scales. The perceived slowness of these ecosystems to recover, and the need for estimates of a 30-year mining operation, will require adequate temporal data, including after an impact, with monitoring recommended to occur on a logarithmic scale: 0, 1, 3, 10, 20 years. Effective monitoring plans and risk management rely on what those longer-term natural changes are likely to be. There were also a few respondents that stated that any amount of time on human timescales would not be an adequate period for closing key scientific gaps given that most vulnerable areas have not yet been explored and that the collection of data should occur on scales which are relevant to the ecosystem being sampled. A suggested alternative would be to assume that the impacted area will never recover, and no rehabilitation or restoration will occur, as then temporal sampling and monitoring are not needed, with the focus placed on spatial management instead.

4. Discussion

4.1. Scientific gaps and the fast-tracking of an emerging industry

Deep-seabed mining, if it moves forward, will be a new industry in a relatively unexplored part of the planet. The literature review and stakeholder survey described in this study reflect a host of scientific knowledge gaps that must be addressed as a precursor to effective management in accordance with the environmental obligations set forth in UNCLOS (Fig. 1). Even the most well-studied habitats of the deep ocean (e.g., active vents on the MAR) are still characterized by a paucity of information concerning the ecology and connectivity of deep-sea species and ecosystems, their roles in the provision of ecosystem functions and services, as well as the scope and scale of mining's potential impacts. Given that deep-sea scientific research is challenging as well as time and resource-intensive, closing these gaps is likely to require substantial time and a capacity-intensive, coordinated scientific effort.

Deep-seabed mining's proponents seek to move forward with their operations in the near-term. On June 25, 2021, one of the ISA's Member States, the Republic of Nauru, notified the ISA of its invocation of a rule requiring the ISA to complete negotiations over exploitation regulations in two years, or otherwise evaluate applications for plans of work submitted thereafter based on provisional rules and the UNCLOS. In light of this development, it seems highly unlikely that the necessary research can be completed within this timeframe, even if gaps that are critical for elucidating environmentally acceptable thresholds to manage this industry are prioritized.

4.2. Closing the scientific gaps: a proposed road map

Recognizing the scope of investigation still required, collaboration, under the direction of strategic and regional environmental goals and objectives, will be needed. Below we propose a *potential* road map for closing the key scientific gaps related to deep-seabed mining in ABNJ (Fig. 2) that was compiled using the results of the literature review and the stakeholder consultation, as well as the action plan of the ISA in support of the United Nations Decade of Ocean Science for Sustainable Development [297]. This road map offers nine stages for ameliorating identified knowledge gaps related to deep-seabed mining under timelines based on estimates from survey respondents. These timelines will be influenced by capacity and resources invested in the relevant research, including by contractor contributions to regional research initiatives. Our intent is that this *potential* road map will stimulate debate and ultimately result in a more strategic and coordinated

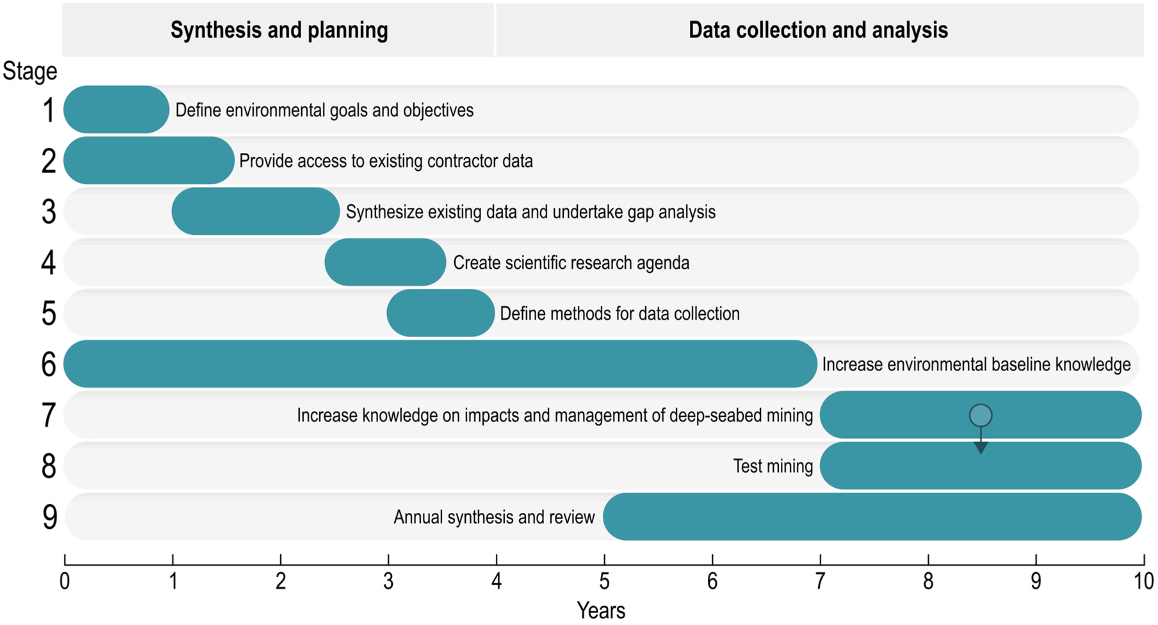


Fig. 2. A proposed road map for closing key scientific gaps related to deep-seabed mining. This road map is applicable to any resource (polymetallic nodules, polymetallic sulfides, cobalt-rich ferromanganese crusts) in any relevant region (Clarion-Clipperton Zone, Central Indian Ocean Basin, West Pacific, Mid-Atlantic Ridge, Indian Ocean Ridges, West Pacific Prime Crust Zone, South Atlantic Rio Grande Rise). It is broadly anticipated that a decade (or more) could apply to each resource in each region. Regions with more scientific knowledge than others (e.g., the Clarion-Clipperton Zone) may require less time. This process can occur concurrently for each resource in each region shortening the potential multidecadal timeframe, although this will depend on resources available.

approach for filling these scientific gaps.

Ideally the proposed road map would be facilitated by the ISA, in coordination with the Intergovernmental Oceanographic Commission and consistent with the goals and aspirations of the UN Decade of Ocean Science for co-development, capacity building, and technology development. However, it would necessitate the expertise of an additional collaborative scientific committee or an informal expert working group.

The proposed road map seeks to identify, compile, and make available, in the most expedited manner possible, the scientific understanding that most experts have deemed to be essential for informed decision-making. It also assumes that the precautionary approach will be applied throughout [298]. It should also be noted that the proposed timeframe for the period of scientific study should not prevent the concurrent development of the regulatory framework or the advancement of technologies to monitor, measure, and minimize potential impacts to the maximum extent possible.

Undertaking this road map should be an international and widely consultative process that builds upon the work that has already been undertaken by the ISA. Throughout the process, the ISA would ideally promote the translation, dissemination, exchange and sharing of scientific data and deep-sea research outputs to increase deep-sea literacy. This includes scientific data and information from contractors to scientific experts, as well as packaging relevant scientific knowledge in an understandable way for stakeholder groups, including policymakers and the public. This also includes working with the scientific community to remove jargon and paywalls, as well as publicizing in various languages. Given this is the Common Heritage of Mankind, all stakeholders should be considered “relevant”.

Collaboration is key. Understanding environmental baselines and impacts, and determining thresholds, will only be elucidated through collaboration between the regulator, scientists, engineers, and contractors. This can be facilitated by international research consortia (e.g., JPI Oceans) and/or scientific networks such as InterRidge, the Deep Ocean Observing Strategy (DOOS), and the Deep-Ocean Stewardship Initiative (DOSI). Training and sustaining scientists, and inspiring the next generation of ocean stewards, scientists, policymakers, and managers, is a cornerstone to the success and sustainability of this road map. As such, developing capacity could be woven through every stage. Human capacity can be built through sustained equitable partnerships that include training, education, and mentoring [299,300]. Technical capacity, such as research equipment and research infrastructure, is also needed so that all scientific stakeholders can engage with and benefit from the Common Heritage of Mankind.

Stage 1) Host workshops to define environmental goals and objectives: It is recommended the process begin with a series of essential workshops to define overarching strategic environmental goals and objectives that apply uniformly to all deep-seabed mining activities in ABNJ, and which guide all decision-making, including the identification of knowledge gaps and the approaches to resolving them, and determine the necessary environmental standards of operations (Fig. 2). The development of strategic environmental goals and objectives is needed to subsequently inform the development of regional environmental management goals that could be framed by what will be needed by contractors to close scientific gaps and formulate a robust and comprehensive EIA/EIS and EMMP, and what will be required of the ISA to serve as an effective regulator, including, among other things, rigorous assessment of contractor applications and performance, and commissioning of strategic scientific studies at a regional level. These workshops would be spearheaded by the ISA and Member States but also include scientific experts and environmental managers, as well as a broader spectrum of stakeholders from diverse sectors (e.g., NGOs, IGOs, UN agencies, fisheries, mining, energy, shipping, civil society) as defining what is of most importance is partly a societal question. These should be conducted in an accessible and inclusive way, be followed by a lengthy consultation period, and then sanctioned by the ISA Council. Regional environmental goals and objectives could also be developed through a more formalized REMP process (which should be guided by strategic environmental goals and objectives), with a clear understanding of required content and procedures for development, approval, and review [301–303].

Stage 2) Provide access to existing contractor data: All non-confidential contractor environmental and environmentally-relevant mining-equipment data stored by the ISA Secretariat needs to be made available to all stakeholders so that it can be assessed, analyzed, and used in scientific models (Fig. 2). As identified by the ISA in their scientific research Action Plan, the promotion and facilitation of public access to environmental information and participation by stakeholders will be made possible by DeepData. While DeepData could become an important repository, it is not yet fully operational or integrated with existing global databases. Access should also be provided to bathymetric and non-confidential backscatter data collected by contractors, possibly via the ISA partnership with the Nippon Foundation-GEBCO Seabed 2030 Project.

Stage 3) Synthesize existing data: Considering the strategic and regional environmental goals and objectives identified in Stage 1, all existing data and information thus far produced by the ISA, contractors, and scientists should be synthesized (Fig. 2). This could be undertaken for each region and resource type as early as possible and begin with a comprehensive search and aggregation of data, including usable unpublished contractor data within DeepData (Stage 2), peer-reviewed literature, as well as Indigenous Peoples' science and traditional knowledge [304,305]. This synthesis will then allow for a targeted gap analysis of information most needed for meeting strategic and regional environmental goals and objectives and conducting and evaluating EIAs/EISs and EMMPs. This can be facilitated by annual inclusive meetings of scientific experts (~3–4 days per year), funded by the ISA and/or Member States for each region or resource type, which would enable discussion and synthesis of new findings. Outputs include documents that synthesize and update all the available data for each contract area and region annually. These syntheses could also contribute to the design, implementation, and revision of REMPs in areas with contract areas. Additionally, it can lead to the creation of databases, faunal atlases, species lists, DNA libraries, etc. Contractors, scientists, and other stakeholders should participate in this process, as was observed during the ISA-sponsored 'Deep CCZ Biodiversity Synthesis Workshop' [25], with management potentially undertaken by a scientific committee or the LTC.

Stage 4) Host workshops to determine a research agenda: Following data synthesis and analysis of knowledge gaps, additional workshops will be needed to determine a clear, prioritized, and detailed research agenda, encompassing target and non-target areas for each region where mining may occur (Fig. 2). These workshops will establish sampling and monitoring criteria, guided by clear research questions needed to achieve the strategic and regional environmental goals and objectives identified in Stage 1 and close the gaps identified in Stage 3. A key part of this will include identifying priority ecosystem structure (e.g., biodiversity), functions, and services for preservation. Science needs to coordinate top priorities by working backwards from top functional and structural aspects, finding out who the key players are, what function they support, and then focusing on variability metrics on those key species. As above in Stages 1 and 3, these workshops could also be framed by what is most needed for determining environmentally acceptable thresholds and informing robust EIAs/EISs and EMMPs. These workshops will work towards building synergies, coordinating partnerships, augmenting existing initiatives and avoiding overlaps, leading to the more effective use of available resources. They will need to not only actively engage scientific experts but also a broader spectrum of stakeholders, and ideally be facilitated by the ISA in an accessible and inclusive way, be followed by a lengthy consultation period, and then sanctioned by Member States.

Stage 5) Define methodologies for data collection: As a coordinated research agenda is pursued, methods will need to be standardized across contractors and independent research groups (Fig. 2). The ISA's Strategic Research Priority 2 is the standardization and innovation of robust scientific methodologies and programs for deep-sea biodiversity baseline assessment, including taxonomic identification and description, in the Area [306]. Draft Guidelines have been released by the ISA for the establishment of baseline environmental data [10]. As this is a Guideline (non-binding), there is no requirement for contractors to follow the guidance. Additionally, without clear and defined environmental objectives, indicators, and thresholds, contractors may be amassing a large amount of data without any clear target in mind. It may be appropriate to amend this document once environmental goals, objectives, and indicators have been better defined.

Defining methodologies will significantly improve the collection and analysis of environmental data to assess the potential risks that activities in the Area interfere with the ecological balance of the marine environment. These could include specific standardized minimum requirements on what parameters need to be measured, detailed methodologies to be used (including requirements for meeting statistical robustness), and analyses to be carried out, so that data collection, comparison, and synthesis is as efficient as possible in terms of time, effort, and resources in the Area. If methodologies are not standardized across contractors, it may not be possible to use that data in regional analyses. This would be a loss, given the limited financial resources the ISA has to conduct, or even facilitate, its own regional analyses. Development of these methodology standards should be conducted in an accessible and inclusive way, be followed by a lengthy consultation period, and then sanctioned by Member States. After this, training workshops can assist with developing capacity across stakeholders to establish baselines and monitor impacts.

Stage 6) Increase environmental baseline data collection: Increasing the intensity and frequency of data collection is needed if the ISA's Strategic Research Priority 1 is to be achieved [306] (Fig. 2). A combination of in-situ sampling and observations, remote sensing, ex-situ laboratory experiments, and modeling can be used, and should utilize the best available science, best industry practice, and standardized methodologies (as decided during Stage 5). There should be increased sampling utilizing standardized methods within and near to exploration contract areas by all contractors across all regions, including within APEIs (where existent). This will not only increase the validity and reliability of the research but also allows for comparability and synthesis leading to broader conclusions, and better-informed area-based management. In addition to increased baseline data collection within and near exploration contract areas by contractors, large-scale, replicated, standardized scientific campaigns, coordinated by the ISA, could be undertaken (Table S2). These could encompass both the seafloor and water column so a better understanding of deep-sea ecosystems' structures and functions can be gained. Given this would require a significant increase in funding and would take a substantial amount of expertise, time, and effort (from an already limited pool) if analysis was included, the sampling could be staggered by resource priority.

Stage 7) Increase the collection of data related to the impacts and management of deep-seabed mining: To gain a more accurate prediction on the types and scales of potential impacts of mining activities to the marine environment (ISA's Strategic Research Priority 4), as well as the cumulative impacts from mining activities and other stressors, modeling exercises, lab experiments, and small- and large-scale in-situ tests complete with local and regional monitoring will need to be undertaken (Fig. 2 and Table S3). This could include experiments addressing the effects of chronic disturbance, e.g., exposure to enhanced turbidity and deposition for periods of weeks to months, as well as climate change.

Stage 8) Test mining: Additionally, and during the same period as Stage 7, test mining should occur at each resource type and region to draw quantitative conclusions about impacts to the marine environment and to set environmentally acceptable thresholds (Fig. 2). This includes the spatial and temporal extents of impacts with regards to chronic vs. acute exposure to stressors, validating the findings of predictive models on the sphere of impact, and operationalizing environmental objectives through the establishment of indicators, trigger points, and thresholds. These tests could include, at the very least, multiple component tests undertaken by individual contractors. EIAs, including equipment specifics and details of an independent assessment, should also be required. A synthesis of the outcomes of all component tests and pilot projects could be undertaken to inform full-scale mining modeling. The data generated from the tests should be transparent, made openly accessible, and inform a contractor's EIAs/EISs and EMMPs in accordance with requirements set forth in the regulations and environmental goals and objectives.

It may be determined that after the above information is gathered, full-scale testing will also be required. In an ideal world, a series of workshops will need to be held to plan a joint full-scale mining test, including the location (in an area where a REMP is in place), time (e.g., for one or more years), and method. This could be a Member-State driven process, coordinated by the ISA Secretariat, encouraged by CSOs, and in coordination with contractors. The closer the technology is to what may be used in commercial mining, the more accurate the results will be. Chronic disturbance experiments/monitoring (especially, chronic plume exposure) will be very important. This could be scaled up over time and the area set aside for long-term monitoring (at least decadal).

Stage 9) Review monitoring and management programs: In addition to the need for the continuation of the design, implementation, and revision of the REMPs and other spatial management in all regions with contract areas, there could be a biannual review of the scientific methodologies, as well as the adequacy of the monitoring and management programs, based on baseline and monitoring data to ensure management practices reflect best available science (Fig. 2). This could also include the incorporation of broader data and information, including related to cumulative impacts such as from a changing climate, etc.

4.3. Timeframe, financing, and execution for the proposed road map

Even if the narrowest approach to environmental research is undertaken, the proposed road map will likely take several decades for all resources in all regions. A phased approach with clear goals or benchmarks will keep activities on track despite seemingly lengthy time periods. Each resource in each region will likely take a decade or more. The process for each will be broadly similar but the timeline may vary according to differences among each region and resource. Each should begin with a four-year period for Synthesis and Planning Activities, which once undertaken will streamline future scientific activities (Fig. 2). The CCZ, although at a relatively advanced stage of knowledge, still requires many more years to allow further data collection and test mining, followed by monitoring and analysis. However, the development of mining technology would need to occur quickly to facilitate this. Once all new data and information are synthesized at the end of this period for the CCZ, it should either be deemed that more data is needed, or exploitation can commence. The CCZ should be prioritized given the advanced state of contracts in this area. These timeframes may seem lengthy but to adequately ascertain temporal aspects, such as seasonal variation, as well as estimate recovery and extinction risks, they are necessary to understand. Effective monitoring plans and risk management rely on knowledge of longer-term natural changes. However, it can be assumed that with technological innovation, some of these timeframes may be shortened (but not all as long-term variation will still need to be assessed). Also, the time periods for each resource in a particular region can run concurrently, which would bring their potential date for commencement of exploitation closer, but as these suggested timeframes require a large amount of already limited funding and effort to effect, that may be unrealistic.

The greatest scientific challenge facing deep-seabed mining is shortage of monetary and human resources, i.e., number of people who currently have expertise and sufficient funding to carry out research in the deep sea. Contractors and/or Sponsoring States are responsible for funding and undertaking much of the work needed to close critical scientific gaps related to the environmental baseline as well as component testing within their contract area. Sole support or most of the support for scientific research by contractors and Sponsoring States, however, leaves many critical gaps in scientific knowledge to be filled e.g., taxonomic descriptions, survey and monitoring criteria, cumulative impacts, issues that span large spatial contexts, spatial planning, protected areas and non-target areas, and capacity development. Given the high costs of deep-sea research, combined funding is potentially the best route forward. This could take the form of a joint fund for marine scientific research, orchestrated, and managed by the ISA (or multilaterally) that any stakeholder group could pay into, including contractors and Sponsoring States, Member States, NGOs, and philanthropies. Additionally, days allocated for the use of national or private research vessels could be donated. A further benefit of this system, beyond more efficient use of time, effort, and resources, includes formulating a system that incentivizes those contractors who go above and beyond when undertaking marine scientific research. However, ultimately, the magnitude of resources required could prompt a re-evaluation of the direction of this nascent industry.

Given that the minimum level of knowledge needed has not been gathered for any exploration region or resource yet, this proposed plan aligns with the increasing calls for slowing the transition from exploration to exploitation [5]. This potential roadmap to close knowledge gaps also aligns well with the UN Decade of Ocean Science for Sustainable Development (2021–2030) [296], of which the ISA is a contributor [297].

Funding source declaration

This work was supported by The Pew Charitable Trusts (33788).

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Acknowledgments

We wish to thank Andrew Friedman, Anindita Chakraborty, and Hannah Lily from the The Pew Charitable Trusts' deep-seabed mining team for their assistance in the design of the project, including the questionnaire. Further thanks to the remaining 13 participants in the stakeholder consultation, the two anonymous reviewers, and Dr. Stacey McCormack of Visual Knowledge for the design and creation of the two figures. The work of CRS was supported by the G & B Moore Foundation, JCD was supported by the Benioff Ocean Initiative, TNM was supported by the Minobrnauki of the Russian Federation Agreement (grant no. 075-15-2020-796), LAL was partially supported by NOAA OER (award NA19OAR0110305), and SJ was partially supported through Korea Ministry of Ocean and Fisheries R&D (grant no. 20160099). The work of MH and SG was conducted in the framework of the MiningImpact project, funded by the German Federal Ministry of Education and Research (grant no. 03F0812A to MH) and by NWO-ALW (grant no. 856.18.001 to SG) in conjunction with the Jocand Oceans (JPI Oceans).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2022.105006.

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