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Environmental risk framework and research recommendations for SMS mining in the Norwegian Arctic mid-ocean ridge

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To meet future demands, mineral resources found in deposits along mid-ocean ridges have triggered the interest of the deep-sea mining industry. Comprehensive environmental management regulations are being developed by the International Seabed Authority (ISA) to control the exploitation of seabed areas beyond national jurisdiction. Norway has recently opened its seabed to mining exploration, which may potentially lead to future commercial exploitation of seafloor massive sulfides (SMS) and manganese crusts. Large uncertainties remain about the environmental consequences of such activities and improved knowledge is required to be able to describe and evaluate the associated environmental risks. An environmental risk assessment (ERA) is the process of assessing potential harm to the environment. In this paper, we apply a framework for environmental risk assessment as a mechanism to identify priority environmental knowledge, technology, and practice needed for future SMS mining operations. The ERA framework is aligned with the key elements of the draft ISA regulations and includes how risk terms and principles are understood and used by Norwegian policymakers and authorities. Regulatory draft documents, scientific literature, expert opinions, and an assessment of environmental severity, vulnerability, and value criteria have provided informative bases for the discussed research and development (R&D) recommendations. While the risk framework and associated R&D recommendations are aimed at future mining in the areas of the Arctic Mid-Ocean Ridge (AMOR) under Norwegian jurisdiction, they are also relevant to other areas of SMS exploitation and may form a useful template.

KEYWORDS

deep-sea mining, seafloor massive sulfides, environmental risk assessment, environmental risk framework, research and development recommendations, Norwegian Arctic mid-ocean ridge

1 Introduction

1.1 SMS mining

Mid-ocean ridges have become a target for deep-sea mining (Weaver et al., 2022). Metal particles dissolved in high-temperature hydrothermal fluids venting from discrete active volcanic centers can precipitate on or beneath the seafloor, forming seafloor massive sulfides (SMS) deposits. These deposits may be rich in metals, including zinc, lead, copper, gold, and silver (ISA, 2022a), however many do not contain commercially viable quantities of ores (Petersen et al., 2016). Watari et al. (2021) have critically reviewed the needs for major metals, supplies and environmental impacts.

In most areas of the world, the mid-ocean ridges lie in areas beyond national jurisdiction and are administered by the International Seabed Authority (ISA). In recent years the ISA has signed seven contracts for exploration for SMS deposits, of which three are in the North Atlantic Ocean. Areas of the Arctic Mid-Ocean Ridge (AMOR) under Norwegian jurisdiction were in 2024 formally opened by the Norwegian government for exploration activities and environmental knowledge acquisition for possible deep-sea mining (Norwegian Government, 2024).

Sulfide mounds and chimneys are formed at the seabed and colonized by fauna dependent on the microbial chemosynthetic primary production fueled by the venting fluids (Tunnicliffe et al., 2003). The vent-endemic fauna is restricted to active vents aligned in a narrow band along the mid-ocean ridge axis and thus covers very limited areas globally (Rogers et al., 2012). Different ridge systems also host different organisms, and Rogers et al. (*ibid.*) identified 11 different biogeographical zones on ocean ridges. Thus, the areal extent of each biogeographical zone may be very small.

The AMOR supports a specialized vent fauna distinct from that in other ocean regions (Eilertsen et al., 2024). The unique hydrothermal vent faunas could be impacted by SMS mining, either directly through the removal of the hydrothermal mounds and chimneys, or by changes to the vent fluid flow thus cutting off the supply to particular communities (Washburn et al., 2019).

There is, however, a strong possibility that SMS mining will focus exclusively on inactive vents, for which little information is available regarding their biodiversity, connectivity, and functioning (Van Dover et al., 2020). However, several studies have shown that the inactive vents are often inhabited by diverse megafaunal assemblages (Ramirez-Llodra et al., 2020, 2024), similar those of the wider ridge axis and thus not restricted in aerial extent. However, sediment-laden plumes could spread from the mine sites, potentially smothering vent and near-vent biological communities some distance away (Levin et al., 2016a; Weaver and Billett, 2019; Ramirez-Llodra et al., 2020). Sediment plumes could also spread to other areas beyond the mining sites where they could impact vulnerable marine ecosystems (VMEs) such as cold-water coral reefs (Roberts et al., 2006; Mienis et al., 2009; Brooke et al., 2009) or deep-sea sponge grounds (Kutti et al., 2015; Hanz et al., 2021; Meyer et al., 2023). The feasibility of SMS mining may thus include environmental costs added to economic profitability as compared with land-based sulfide deposit mining and metal recycling.

1.2 Governance

The ISA is currently developing its mining code to manage and control the activities of mining contractors in areas beyond national jurisdiction (ISA, 2019). The status of the draft regulations is available on the ISA website (ISA, 2023), together with a series of standards and guideline documents that will accompany the regulations. At present, 31 contracts for the exploration of mineral resources (including manganese nodules, cobalt-rich ferromanganese crusts, and SMS) have been signed by the ISA, but no applications for commercial mining have been made so far.

All States parties that are signatories to the United Nations Convention on the Law of the Sea (UNCLOS), including Norway, must develop laws and regulations that are not less effective than the ISA's mining code as set out in UNCLOS (United Nations, 1982). Norway has the jurisdiction over large seabed areas on the AMOR containing SMS and manganese crust deposits seen as potential sources of critical minerals (Norwegian Petroleum Directorate, 2023) and should, as a signatory to UNCLOS, apply the ISA's regulations as a minimum standard.

In Norway, a governmental administrative opening process for deep-sea mineral exploration has been approved (Norwegian Government, 2024) based on a preliminary Environmental Impact Assessment (EIA) (Norwegian Petroleum Directorate, 2022) and recommendations given in Norwegian Report to the Storting (white paper) (Norwegian Government, 2023). The first licensing round was postponed in 2024/25 due to political disagreement over national budget priorities. On condition that the licensing round reopens in a later budget period a commencing step is expected to involve an exploration phase for further knowledge gathering.

Abbreviations: SMS, Seafloor massive sulfides; AMOR, Arctic Mid-Ocean Ridge; VME, Vulnerable Marine Ecosystems; EBSA, Ecologically or Biologically Significant Area; Organizations: ISA, International Seabed Authority; UNCLOS, United Nations Convention on the Law of the Sea; CBD, United Nations Convention on Biological Diversity; FAO, Food and Agriculture Organization of the United Nations; CCAMLR, Commission for the Conservation of Antarctic Marine Living Resources; U.S. EPA, United States Environmental Protection Agency; SRA, Society for Risk Analysis; Risk terms: EIA, Environmental Impact Assessment; EMMP, Environmental Management and Monitoring Plan; ERA, Environmental Risk Assessment; RS, risk source; α, activity; A, events/hazards/threats; C, consequences (impacts); C_A, consequences (impacts) of events; τ, time period over which an activity is observed; η, length of time over which consequences of occurred events is evaluated; U, uncertainty; RS', specified risk sources; A', specified events/hazards/threats; C', specified consequences; C_A', specified consequences (impacts) of specified events; Q, characterization/measure of uncertainty for specified consequences; K, background knowledge that the specification of C' and Q are based on; SoK, strength of knowledge; WoE, weight of evidence (in ecological assessments); RI, risk indicator; monitoring parameter for evaluating changes in the risk or the state of the environment as an operation progresses over time.

Current Norwegian offshore regulations, initially aimed at petroleum activities, require the management of offshore activities to be risk-based, which must include all operators' assessments of environmental risk. Environmental research and development (R&D) needs must be identified and prioritized in order to reduce knowledge gaps that contribute strongly to the presently high levels of environmental risk associated with future SMS mining activities.

An environmental risk assessment (ERA) is "the process of assessing potential harm to the environment caused by a substance, activity or natural occurrence" (European Food Safety Authority, n.d). The present paper applies a framework for environmental risk assessment of offshore SMS mining operations in Norwegian areas. This framework may serve as a structured foundation for defining and recommending priority R&D topics and will also have relevance to other geographical regions with similar mining initiatives. This type of use, as a tool to systematically identify and prioritize knowledge, technology, and practice needs, represents a novel application of this framework.

1.3 Method requirements and challenges

The preliminary requirements of the Environmental Risk Assessment (ERA) for the future deep-sea mining code applicable to areas beyond national jurisdiction have been extensively described in the draft standards and guidelines for the environmental impact assessment process by the ISA (2022b). Although not yet approved, this should be the starting point for all national work related to the actual type of mineral and mining activity, and the environmental context. National regulations could exceed the ISA requirements.

A key requirement in the ISA's draft mining code is for the ERA to serve as an integrated part of the Environmental Impact Assessment (EIA) process, leading to Environmental Impact Statements in the different mining projects. The overall objective of the ERA is to serve as a tool for focusing on the key environmental issues and to check whether available data are sufficient in the subsequent EIA and Environmental Impact Statement. The risk evaluation and description will typically be connected to questions about what can cause unwanted events and consequences, about their uncertainties, and if there is sufficient knowledge informing management measures for prevention, mitigation, and restoration. The ERA should address environmental risk related to regular operations as well as accidental incidents.

Hence, the ERA process has a particular early phase importance but also should be a tool actively used to assess the projects' environmental planning and performance throughout their duration. Upgraded ERAs should serve as important checks to ensure the EIA is focused on the activities and aspects of impacts and consequences that pose the most risk to the environment (Clark et al., 2020; ISA, 2022b).

The purposes of the ERA defined by ISA are important to the present paper's discussion about R&D needs, therefore they are shortly described below with reference to ISA (2022b, 2023).

The ERA should be initiated in the EIA scoping process when undertaking a preliminary impact analysis. This should be updated as the EIA proceeds.

Specifically, the EIA process includes:

- an ERA that considers the region as a whole (ref. 'regional environmental management plan'),
- a preliminary ERA during scoping,
- available results from 'test mining',
- an ERA that adds to the preliminary ERA during scoping,
- identification of scientific and other knowledge gaps or data uncertainties and assessment of the degree to which these influence the EIA.
- identification of measures (including monitoring, mitigating and managing) to keep effects and risks as low as reasonably practicable (and within environmental 'standards', etc).
- an ERA result analysis, including identification of risks requiring particular focus.

This contributes to the basis for:

- 'Environmental monitoring' that aims to measure, evaluate and analyze the environmental thresholds (contained in 'standards') and the risks to 'environmental effects', and
- 'Environmental management and monitoring plan' (EMMP) that will set out procedures on how to monitor, mitigate and manage the 'environmental effects' and risks, including pollution control and 'mining discharge'.

The ISA does not prescribe a particular method for the ERA, as different methodologies may have varying relevance in particular mining contexts and areas. Historically in Norway, ERA methods for offshore activities (such as for hazards related to operationally and accidentally released chemicals in the marine environment) often rely on model-based methods simulating exposures and on standardized ecotoxicity tests to inform about the potential impacts. The combined information is then used to characterize consequences and risks (e.g. Reed and Rye, 2011; Smit et al., 2011). The state of knowledge is currently much weaker for activities in deep-sea environments. Knowledge gaps are, on the one hand, related to how deep-sea mining will be conducted technically and, on the other hand, how it will influence environmental conditions and complex processes caused by multiple sources or chains of events and, subsequently, their influence on biological communities. In combination, this leaves an uncertain basis to define event scenarios and evaluate associated consequences. Hence, ERA of deep-sea SMS mining will require a strong emphasis on the methodology for handling uncertainty related to several risk factors in complex systems.

In complex cases, impacts of one event may indirectly lead to others, or impacts of different events may combine into more severe effects depending on several environmental factors, including temporal and spatial variations. Such situations may cause cascading and cumulative effects that must be taken into consideration in deep-sea mining activities (Van Dover, 2014; Levin et al., 2016b; ISA, 2022b). It must be possible to handle such complex effects within the ERA framework proposed herein. Moreover, cumulative impacts may potentially occur by interaction between different mining projects or with other anthropogenic sources of change to the marine environment (i.e. resource extraction, climate change) and cause effects at a regional level. These should be taken into consideration in each project's environmental assessments to the extent allowed by available information (ISA, 2022b).

While such complex assessments of ecosystem health and harm cannot be well achieved from current evidence-based knowledge of deep-sea habitats and resources (Levin et al., 2016b; Amon et al., 2022), it seems clear that this situation must be improved by generating relevant research-based knowledge before commencement of commercial SMS mining. The objective is to obtain general key environmental risk and impact-related data in combination with area-specific knowledge to be gained during the early phases (scoping) of mining projects.

Different environmental risk aspects of deep-sea mining have been suggested and discussed in earlier and recent scientific literature (Ahnert and Borowski, 2000; Van Dover, 2011; Jones et al., 2018; Cormier and Londsdale, 2019; Washburn et al., 2019; Clark et al., 2020), and evaluation of risks to seabed ecosystems associated with inactive and extinct SMS deposits (sensu Jamieson and Gartman, 2020) through targeted research has been called for (Van Dover et al., 2020).

Recent papers have focused on a management framework and how to define serious harm and thresholds in relation to deep-sea mining (Hyman et al., 2022b; Hiddink et al., 2023; Hitchin et al., 2023; Leduc et al., 2024). Amon et al. (2022) proposed activities stimulating the discussion necessary to close key scientific gaps before considering any exploitation.

The discussion of R&D priorities herein is along with the above-cited papers, Norwegian government documents with associated expert opinions, and ISA's proposed draft regulation requirements (2022b), based on criteria for severity of consequences related to environmental value, vulnerability and determination of serious harm (see Section 2.1.7). Our proposed risk assessment framework with associated knowledge gaps and priority R&D recommendation is based on a targeted policy and practice review of this information.

2 Policy/guidelines options and implications

2.1 Risk framework

2.1.1 Conceptualizing risk

Due to the present weak state of knowledge and the uncertain basis for defining event scenarios and evaluating consequences, a well-suited risk perspective for ERA of deep-sea SMS mining needs to include uncertainty in the definition of environmental risk. This creates the opportunity to include characterizations of uncertainty other than the traditional probability-based description of the risk. This approach aligns with recent perspectives in risk science where uncertainty is explicitly included as a core component of risk, and probability is merely one of many tools that can be used to express uncertainty (Aven and Zio, 2011; Flage et al., 2014).

2.1.2 Risk concept definition

According to the perspective described in Section 2.1.1, the concept of risk can generally and qualitatively be defined as "uncertainty about and severity of the consequences [including events and impacts/effects/outcomes] of an activity concerning something that humans value" (Aven and Renn, 2009; SRA, 2018; Aven, 2019). Maintaining a healthy environment offers value to mankind, including ecosystem services for human benefit and for sustaining ecological functions and structures (Rees et al., 2022).

The Norwegian Ocean Industry Authority (2024) defines "risk" as "the consequences of the activities, with associated uncertainty". The term "consequences" is here used as a collective term for all consequences of the activities. The term is not solely limited to the final consequences of the activities, but also includes conditions, incidents and impacts and complex effects that can result in or lead to this type of consequences. These meanings of the terms "risk" and "consequence" are adopted in the present paper.

In their draft regulations, the ISA defines an "impact" as "the influence of an action/activity during the [mining] project on the environment". An "effect" is defined as "the consequence or outcome of an action or activity during the [mining] project". It is typically broader and more functional than an "impact" (ISA, 2019).

In our risk framework, we use the ISA meaning of "impact" and "effect" terms for consequences, while for clarity we emphasize the important distinction in their meanings by respectively using the terms 'direct impacts' and 'complex effects'.

Hence, the "consequence" term in our framework consists of one or several different 'direct impacts' in various combinations, leading to more 'complex effects' of different spatial and temporal kinds and extents. The latter is sometimes referred to or associated with the terms "networks" or effects having "combined risk sources" or "causal chains of events", which may also refer to cumulative consequences from one or more interacting operations (ISA, 2019, 2022b).

Hence, the environmental risk in deep-sea SMS mining activity is defined in relation to harmful consequences on habitats and biota and the uncertainties about these consequences. The major focus will be on the potentially affected deep-sea ecosystems, without overlooking potential effects at all depths of the water column above the mining areas.

2.1.3 Components of the risk concept

In our concept, for a given "activity", we have defined the risk components "event/hazard/threat" and linked them with "risk source" and "consequence". These components are commonly included in risk concepts to provide structure for linking different risk data and forming adequate frameworks to support risk descriptions for good managerial practice.

The structure is also made with the aim to handle emerging information, such as evidence-based knowledge of complex effect consequences. An expected development from qualitative to more quantitative risk information is expected, and emerging research data on ecosystem structures, processes and vulnerabilities will facilitate more systematic and detailed descriptions of deep-sea SMS mining risks than what is possible today. This will gradually allow for better discrimination between 'direct impacts' and broader and possibly more severe 'complex effects'.

In the following, a more formalized definition of the risk concept and its description (measurement) is briefly explained and exemplified by some assumed key risks related to deep-sea SMS mining activities.

According to the definition in Section 2.1.2, risk as a concept has two dimensions: the consequences (C) of an activity (α) and the uncertainty (U) associated with these consequences, schematically expressed as risk = $(C,U)_{\alpha}$. Here, C refers to the actual future consequences, which will be uncertain before the activity is carried out, indicated by the U component.

Examples of consequences (C) can both be 'direct impacts' (such as biological disturbances or physical/chemical habitat destruction) caused by single sources and events, or by multi-sources or chains of events yielding 'complex effects' on broader magnitude or scales. C can be subdivided into risk sources (RS) (e.g., excavated sediment in suspension), events/hazards/threats (A) (e.g., particle spreading and re-sedimentation), and the resulting consequences (impacts and effects) of these events (C_A) (e.g., ecotoxicity, organism burial, habitat removal, species extinction, etc.). Schematically, this can be expressed as C = (RS,A,C_A), and the risk concept can thus be reformulated as risk = $(RS,A,C_A, U)_{\alpha}$. (Figure 1).

Due to general slowness in deep-sea ecological processes (see further Section 2.2.2) it will be important to consider the temporal aspects of the events/hazards/threats and their short- and long-term consequences. At least two temporal considerations are important in a risk assessment (Logan et al., 2021):

1. The period of time over which the activity is observed (τ), and
2. time interval during which we evaluate the consequences after an event has occurred (η).

The temporal aspects can be explicitly included in the schematical formulation of risk as Risk = $(RS,A,C_A,U)_{\alpha\tau,\eta}$ (Figure 1). Temporal aspects are of particular importance in the risk concept to capture 'complex effects'.

2.1.4 Components of the risk description

The definition in Section 2.1.1. is of the concept of risk. A description (or measurement) of risk, on the other hand, comprises specified consequences (C'), including specified risk sources (RS'), specified events/hazards/threats (A'), and specified consequences (impacts/effects) of A' (C_A'); a measure/characterization of uncertainty (Q) for the specified consequences, e.g. probability; and the background knowledge (K) that the specification of C' and Q are based on, including assumptions, data and information, models, etc. (Figure 2).

The distinction between C and C' (and between RS and RS', etc.) formalizes the notion that a consequence C may occur during the activity that was not among the specified consequences C' in the risk assessment performed prior to the activity. Analogous to the schematic formulation of risk, we can formally write risk description = $(RS',A',C_A',Q,K)_{\alpha\tau,\eta}$, where C_A' can be composed of different specified impacts/effects (Figure 2).

Generally, a simple risk description can be a categorization of activities and potentially occurring events/hazards/threats and associated potential environmental consequences. To envision some key features of the ecological risk related to deep-sea mining as it currently appears, reference is made to Washburn et al. (2019), who made an initial overview of risk for such activities. A list of "risk categories" (comprising events and impacts) and "risk sources" was generated based on expert opinions regarding deep-sea mining for different resources (*ibid.*).

We adopted their term "risk source" to serve as a component in our risk concept (Section 2.1.3) and included their examples of "risk sources attributed to sulfides" in our risk descriptions (RS') (with some additions to their list) (Section 2.2.1).

Given limited possibilities at present to use models and probabilities to characterize the risk level, both qualitative and semi-quantitative characterizations must be used for the representation of uncertainty in the risk descriptions for deep-sea SMS mining (Clark et al., 2020).

2.1.5 Uncertainty description; measure of uncertainty (Q), and background knowledge (K)

In our framework, uncertainty is integrated into the present risk model and described in association with each risk source (RS'), event/hazard/threat (A') and consequence (C_A'). This will add clarity to the risk analyses and descriptions. Having specified (RS', A', C_A'), uncertainty about the future occurrence of these risk sources, events and consequences is described using some uncertainty measure (Q), based on some background knowledge (K), covering assumptions and evidence (data, information, testing results, etc.) (SRA, 2018), as illustrated in Figure 2. Clark et al. (2020) discusses types of uncertainty and management in relation to EIA for deep-sea mining with high relevance also for ERA.

Which approach risk analysts choose to use for the uncertainty descriptions is left open in our framework. The key importance is that uncertainty characterizations and measures are of appropriate types and provide as accurate descriptions as possible for the risk evaluations to support adequate managerial decisions. Hence, risk mitigation by reduced uncertainty resulting from well-targeted research should be aimed for (ref. Section 2.2).

2.1.6 Uncertainty description; strength of knowledge and weight of evidence

In our proposed risk framework, the strength of the background knowledge (SoK) must also be evaluated for managerial decisions (e.g., how representative and comprehensive the data set is) as a part of the uncertainty description (Q) (Figure 2). Such an evaluation is not trivial since knowledge based on different kinds of data must be

10.3389/fmars.2025.1651042

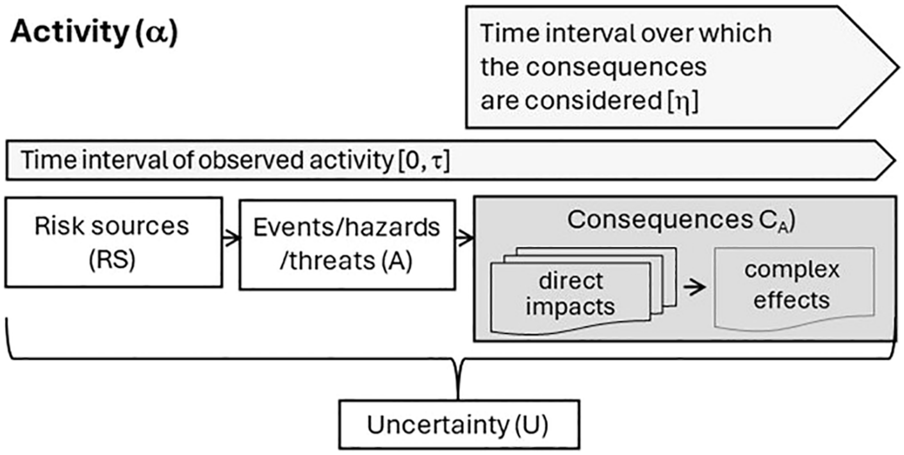

FIGURE 1
Illustration of the risk concept represented by $(RS,A,C_A,U)_{\alpha\tau,\eta,}$ where the consequences (C_A) of events/hazards/threats (A) arising from risk sources (RS) are seen in relation to an activity (α) over the time interval [0, τ] and where η specifies the time over which the consequences (C_A) are considered, following the occurrence of the event (A), and the associated uncertainty (U).

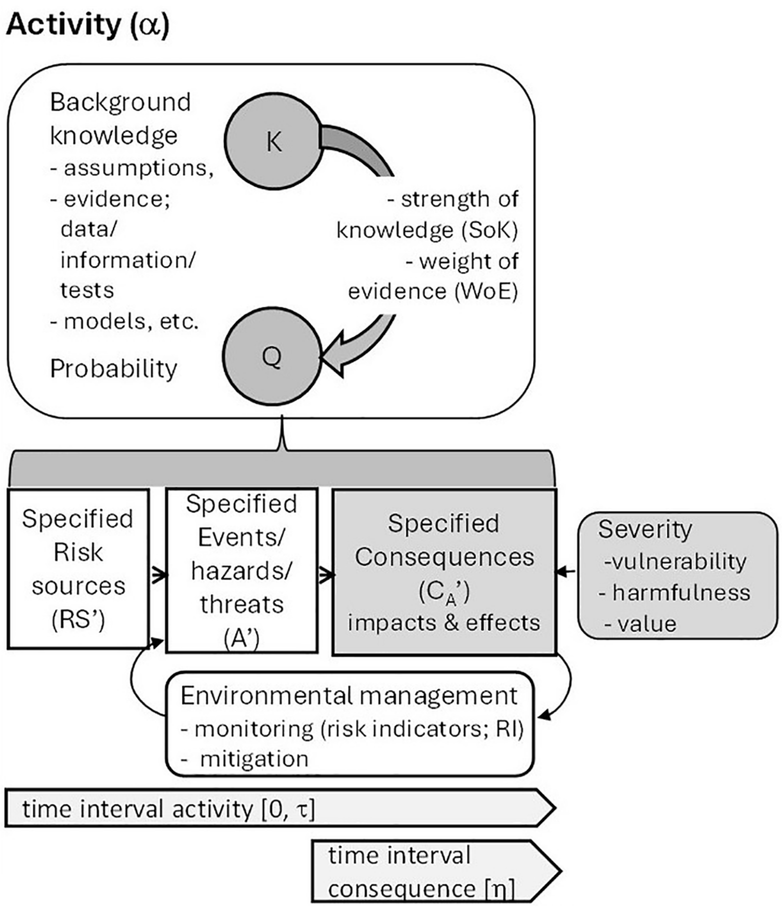

FIGURE 2
Illustration of the risk description represented by $(RS',A',C_A',Q,K)_{\alpha\tau,\eta}$ meaning specified consequences (C_A') related to specified risk sources (RS') and specified events/hazards/threats (A'), associated with an activity (α) over the time interval [0, τ] and where η specifies the time over which the consequences are considered, following the occurrence of the event, and a characterization/measurement of uncertainty (Q), and the background knowledge (K). Relationships with severity and strength of knowledge evaluations, and environmental management activities are indicated.

combined and compared when dealing with problem-solving related to specific cases.

A simple approach to describe confidence (uncertainty) rating is based on Clark et al. (2017) and provided as an example by ISA (2022b). Other specific applications of SoK characterizations have, to our knowledge, not yet been made for deep-sea SMS mining; however, some approaches for how to conduct combined SoK characterizations and apply weight to different knowledge kinds and items can be found in risk analytical literature, e.g. Askeland et al. (2017) and Aven and Flage (2018).

A general approach for weighing various kinds of evidence (knowledge) in ecological assessments (including predictive risk assessments) is the 'weight of evidence in ecological assessments' (WoE) (U.S. EPA, 2016). The approach recognizes that risk assessment may rely on qualitative knowledge and is a flexible, non-prescriptive tool regarding different areas of application. However, it provides consistency across different applications, emphasizing causal evidence, and can be used from the problem formulation in a scoping to the final risk evaluation, conclusion, and communication. It can be applied to risk elements from single pieces of evidence (e.g., ecotoxicity tests, sub-lethal adverse effects, pollutants bioavailability) (Piva et al., 2011; Hauton et al., 2017) to bodies of evidence applying to more complex hypotheses (e.g., species local extinction) (U.S. EPA, 2016). Hence, the approach can be useful in improving the knowledge base/body of evidence related to causes and impacts in the presently unpredictable chains of events and cascading effects that may occur in complex deep-sea ecosystems.

2.1.7 Severity; criteria of vulnerability, harmfulness, and value

The severity of consequences is a key element in the risk description (Figure 2). Identification of environmental vulnerability and value and criteria to characterize and evaluate the severity are needed for risk assessments.

For areas that can be affected by SMS mining, such criteria are currently lacking. Procedures are under development to define serious harm in relation to different kinds of deep-sea mining activities (Levin et al., 2016b; Leduc et al., 2024; see below). However, generic sets of environmental vulnerability and value criteria established for the marine environment by international organizations can, for the time being, be used in the risk assessment framework (Table 1), to be made more adequately detailed as new knowledge emerges.

Specific established sets of criteria that should provide useful guidance in the evaluation of environmental vulnerability and values for SMS mining are two 'VME' (vulnerable marine ecosystems) sets and one 'EBSA' (ecologically or biologically significant areas) set. The objectives behind these differ as the 'VME's are fisheries management-oriented, and the 'EBSA' is developed for recognizing areas of the open ocean and deep sea with special importance in terms of ecological and biological characteristics in the context of biodiversity conservation.

One 'VME' set was developed by the Food and Agriculture Organization of the United Nations (FAO, 2009) related to the management of deep-sea bottom-contacting fisheries, and will undoubtedly have strong relevance to deep-sea SMS mining (Levin et al., 2016b).

The other 'VME' set made by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) (Ardron et al., 2014) is similar, but with additional consideration of motility and larval dispersal, adding to the relevance of SMS mining.

The 'EBSA' set was put in place by the United Nations Convention on Biological Diversity (CBD) in 2008 (CBD, 2008, 2009; Clark et al., 2014; Ardron et al., 2014) and among others recognizes areas providing essential habitats, food sources or breeding grounds for particular species (Rice et al., 2022).

The 'VME' and EBSA' criteria are similar but with notable differences (Rice et al., 2022). For example, the different criteria sets use different terminology, however, expert reviews by the FAO and CBD concluded that similar data can be used for both 'VME' and 'EBSA' criteria, and that the approaches complement one another (Ardron et al., 2014; see also Smith et al., 2020). The three criteria sets are listed here comparatively (Table 1). Ardron et al. (2014) discuss further details of the definition and a 10-step framework for their use, with weight on the 'VME' criteria. Regulatory implementation by ISA is ongoing.

Besides the identification of areas of environmental value and vulnerability, for assessment of environmental risk it will also be necessary to define potentially harmful effects to any structural ecosystem component that may be affected ("receptors") by an activity in the affected areas. Leduc et al. (2024) have proposed an approach towards defining "serious harm" for management of seabed mining, distinguishing receptor characteristics in terms of (i) spatial distribution, (ii) sensitivity, and (iii) ability to recover. This is a highly relevant and useful approach for the characterization of severity of consequences that can be further developed and used in our risk description (Figure 2). Leduc et al. *(ibid.)* emphasize that not only the impacts on receptors associated with deep-sea mining should be considered, but also the characteristics of the activity or disturbance to characterize the full extent of environmental effects. This linkage corresponds well with the risk components of activity and event/hazard/threat in our risk concept and description (Figures 1, 2).

2.2 Knowledge gaps and risk mitigation

The current background knowledge for inactive polymetallic sulfide ecosystems is very scarce, and few studies have been published on their characterization. These ecosystems have one of the highest knowledge deficiencies of any deep-sea mining resource areas, regarding both abiotic and biotic baselines as well as potential mining impacts, resilience and management (Amon et al., 2022).

Much improved knowledge about the consequences and their causes will be required for adequate environmental risk- and impact assessments of deep-sea SMS mining (ISA, 2022b). To close all knowledge gaps will not be realistic, therefore prioritization of the initially most relevant and important data will be needed to assess the environmental risks.

Since uncertainty is an integrated component of risk as conceptualized here, strengthened background knowledge may

TABLE 1 VME (FAO), VME (CCAMLR), and EBSA (CBD) list of criteria for value- and vulnerability identification. Sources: FAO (2009); CCAMLR (2009); CBD (2008, 2009).

VME (FAO)	VME (CCAMLR)	EBSA (CBD)
Uniqueness or rarity	Rare or unique populations	Uniqueness or rarity
Functional significance of the habitat	Habitat-forming	Special importance for life history stages of species
		Importance for threatened, endangered or declining species and/or habitats
Fragility	Fragility	Vulnerability, fragility, sensitivity, or slow recovery
Life-history traits of component species that make recovery difficult	Slow growth	
	Larval dispersal potential	
	Longevity	
	Lack of adult motility	
Structural complexity	Habitat-forming (as above)	*
*	*	Biological productivity
		Biological diversity
		Naturalness

Table excerpted from Ardron et al. (2014).
*No explicit comparable criterion.

contribute to mitigate (reduce) the assessed risk. At a high level of epistemic uncertainty (due to the present lack of knowledge), the overall environmental risk must currently be considered high. The low level of developed technology for deep-sea SMS mining adds to this.

The approach herein to clarify and potentially mitigate current risks based on scientific evidence and technological know-how, is to use our proposed risk framework to identify and prioritize R&D activities for recommendation in the present early development phase of deep-sea SMS mining.

For these recommendations, the important aspects of time and space make it useful to separate between R&D related to 'direct impacts' resulting from single risk sources/events, and 'complex effects' resulting from multiple risk sources/events that develop over longer time and larger regional scales. These are presented respectively in Sections 2.2.1. and 2.2.2. and Tables 2, 3.

2.2.1 'Direct impacts'

Important environmental risks related to 'direct impacts' of deep-sea SMS mining are summarized in Table 2. These identified risks are attributed to expected activities (α; 1.col.) and associated risk sources (RS'; 2.col.) in the mining process that can cause events, hazards, or threats (A'; 3.col.) with potential harm to the marine environment. These are further linked to the associated 'direct impact' consequences (C_A'; 4.col.) potentially affecting single organisms, species or local communities.

References to experts' opinions about environmental consequences in scientific literature are given in Table 2; 5.col.). Most consequences listed in the table were also expressed by experts in the initial EIA program proposal hearing in Norway (Norwegian Government, 2021a; cf. Lukoseviciute, 2022).

Although there seems to be consistency between experts' opinions about the listed potential impacts in Table 1, it should be strongly emphasized that important scientific data and technical know-how are still lacking for a more evidence-based identification and quantification of the impacts of deep-sea mining (Ramirez-Llodra et al., 2011; Levin et al., 2016a, b; Van Dover et al., 2020; Norwegian Offshore Directorate, 2024) with underlying knowledge base reports (Norwegian Government, 2021b, c). Generation of new experimental or empirical data to support verification and quantification of the currently identified risks is discussed in Section 3.1.

2.2.2 'Complex effects'

The described sets of risk in Table 2 have relatively simple pathways from activity to outcome and appear currently identifiable and to some degree predictable. Potential risks associated with broader effects attributed to combined risk sources or chains of events are, on the other hand, far less identifiable and predictable.

It seems reasonable to consider that multiple/combined risk sources and networks/chains of events leading to such broader effects will initially tend to be triggered by simple events/hazards/threats yielding 'direct impacts', as is identified in Table 2. However, under the influence of other activities, changing conditions or additional environmental pressures they may lead to other linked processes involving causal chains of events and impact pathways that are far less predictable and potentially yield broad kinds of cascading and cumulative consequences (Van Dover et al., 2014; Clark et al., 2020; ISA, 2022b) as we herein call 'complex effects' (Table 3). Their possible contributions to consequences and risks include potential harm regarding habitats, toxicity, local populations, rare or valuable species, biodiversity, as well as ecological functioning and ecosystem services, described in Table 3.

Important reasons for concern about such 'complex effects' are poor predictability of pathways and intermediate impacts, considering the sparse environmental background knowledge

TABLE 2 Potentially important environmental risks associated with deep-sea SMS mining, described by risk sources (RS'), events/hazards/threats (A'), and consequences (C_A') of 'direct impacts' associated with different expected activities (α).

Activity (α)	Risk source (RS')	Event/hazard/ threat (A')	Consequence (C_A') – 'direct impacts'	References
Site preparation - substrate removal	Translocated overburden	Organism removal at mining site/ Organism burial at re-deposition site	Benthic organisms/species/community destruction (potentially unrecoverable loss)	Halfar and Fujita, 2002, 2007); UNEP (2007); Yamazaki (2011); Gena (2013)
Excavation of ore	Disrupted or removed seafloor	Substrate and organism disturbance or removal at mining site	Loss of benthic habitats and organisms	Glowka (2000); Halfar and Fujita, 2002, 2007); UNEP (2007); Steiner (2009); Yamazaki (2011); Ramirez-Llodra et al. (2011); Collins et al. (2013); Boschen et al. (2013); Van Dover (2014); Washburn et al. (2019)
	Suspended excavated ore particles	Particle spreading and re-deposition	Ecotoxicity, organism burial, mortality, microbial species/community toxicity	Glowka (2000); Halfar and Fujita, 2002, 2007); Thiel (2003); Steiner (2009); Yamazaki (2011); Woodwell (2011); Ramirez-Llodra et al. (2011); Collins et al. (2013); Boschen et al. (2013); Van Dover (2014); Hauton et al. (2017); Smith et al. (2020)
	Mining gear disturbances/ seafloor alterations/ noise	Strong vibrations and/or loud sounds from machinery	Seabed structure damage from shaking (e.g., reactivation of hydrothermal sources, altered outflow paths). Potential noise effects on biota communication and sensing (e.g., acoustic masking, behavioral disturbance, stress, damaged hearing)	Steiner (2009); Yamazaki (2011); Gena (2013); Boschen et al. (2013); Van Dover (2014); Washburn et al. (2019); Williams et al. (2022)
	Altered and acidified sea floor water flows	Inactive vent chimney removal	Modified fluid flux regimes: changes in distribution, flow rates, chemistry; sulfuric acid leakage, impacts in local organisms/species/communities	Glowka (2000); UNEP (2007); Steiner (2009); Rosenbaum (2011); Ramirez-Llodra et al. (2011); Boschen et al. (2013); Van Dover (2014)
Illuminating activities	Light at depth or surface	Artificial lighting	Potential bioluminescence masking in deep-sea fauna, effects on behavior and interaction in shallow-water fauna	Boschen et al. (2013); Van Dover (2014)
Transport of ore from seafloor to surface	Translocated materials in lift system	Co-transport of organisms, chemicals and riser pipe materials	Loss of larvae and zooplankton in riser, potential health effects of translocated deep-sea organisms and chemicals on shallow communities, potential effects of micro-and nano plastics generated in riser pipe	Gena (2013); Boschen et al. (2013); Van Dover (2014)
Transport of tailings/ return water pumped to sea floor	Returned fine sized tailing plumes	Spreading of fine particles, water and microorganisms in large deep-sea water volumes/ re-sedimenting over large areas	Clogging of suspension-feeding structures and respiratory organs, metal toxicity, fish egg vulnerability, potential health effects by translocated microorganisms and increased temperature	Steiner (2009); Ramirez-Llodra et al. (2011); Gena (2013); Boschen et al. (2013); Washburn et al. (2019); Smith et al. (2020)

available. Spatial and temporal factors add to this, including general slowness in deep-sea ecological processes and expectedly long recovery rates (Van Dover, 2014; Boschen et al., 2016; Clark et al., 2020; Jones et al., 2025). The lack of knowledge about reproductive modes and larval dispersal patterns in the deep sea introduces low predictability to species recovery rates and potential.

With the influence of spatio-temporal factors, the consequences may, in the end, be manifested at various impact magnitudes, ecosystem levels, spatial scales, and with high severity. Further, the inactive hydrothermal vent ecosystems exhibit presently unknown linkages between different biotic components as well as between abiotic and biotic components that may play roles in spatio-temporal processes. For improved predictability of linkages between components and event pathways leading to 'complex effects', adequate plume modelling capability is essential.

3 Actionable recommendations - discussion

3.1 Knowledge improvement - R&D priorities

In the following discussion, it is considered that research to generate knowledge needed for adequate environmental risk assessment should initially focus on tractable, simple relationships between events and consequences associated with a core set of mining activities. Therefore, it seems reasonable to target the first research priorities on processes related to the 'direct impacts' (Section 2.2.1).

It is reasonable to assume that these relationships also will have significance in the complex pathways leading to broader

TABLE 3 Potentially important environmental risks associated with deep-sea SMS mining, focused on possible combined risk sources (RS') and causal chain of events/hazards/threats (A') with potentially broad 'complex effect' consequences (C_A').

Activity (α)	Risk source (RS')	Event/hazard/ threat (A')	Consequence (C_A') – 'complex effects'	References
Ore excavation Transport of tailings	Multiple/ combined risk sources	Networks of unforeseen causal chains of events	Potentially cumulative or complex cascading consequences, hereunder local and regional changes of: *(below)*	Steiner (2009); Van Dover (2014); Levin et al. (2016b)
			Habitats - removal, quality degradation	Halfar and Fujita, 2002, 2007); UNEP (2007); Ramirez-Llodra et al. (2011); Boschen et al. (2013); Van Dover (2014)
			Toxicity - mortality, impairment, reduced fitness due to toxic sediments, metal bioaccumulation, -magnification	Woodwell (2011); Van Dover (2014); Hauton et al. (2017)
			Local populations - elimination or reduction; reduced resilience and fitness. Decreased reproductive output and brood stock. Genetic isolation, reduced population connectivity, species extinctions and invasions	Ramirez-Llodra et al. (2011); Van Dover (2014); Smith et al. (2020)
			Rare or valuable species - local, regional, or global extinction	Ramirez-Llodra et al. (2011); Van Dover (2014); Smith et al. (2020)
			Diversity - decrease (genetic, species, habitat), trophic interactions and complexity, altered community structure	Vrijenhoek (2010); Boschen et al. (2013); Smith et al. (2020)
			Ecosystem functioning – deep-sea pelagic or seafloor alterations; primary production, nutrient cycling, benthic/pelagic coupling, food-chain effects	Van Dover (2014)
			Ecosystem services - loss in benthic or pelagic services (disturbances in habitat, functioning, species, genetics); reduced potential for scientific studies and bioprospecting	Van Dover (2014)

consequences. Thus, the research needed for 'complex effects' will partly depend on the outcome of the herein recommended research and therefore at present be too unpredictable and uncertain to define closely. Consequently, the research priorities discussed herein will mainly be related to the risk descriptions for 'direct impacts', while some general considerations regarding research needs for 'complex effects' are made (Section 3.1.6.).

The discussion of research priorities related to 'direct impacts' must be based on their expected importance, evaluated as severity expressed by vulnerability, value and harmfulness (Sections 3.1.1-3.1.5; Table 4).

The discussion and suggestions herein are made according to available cited expert opinions and judgments made by the present authors considering shortcomings and uncertainties in the background knowledge. The high epistemic uncertainty introduces unavoidable subjectivity, however, by the chosen approach we have strived towards minimizing it. The scientific research should eventually be based on adequate hypotheses to test the assumptions made, and thereby also contribute to reduce the epistemic uncertainty in the risk assessment.

Nevertheless, it must be expected that new research also can yield results of high uncertainty due to methodological investigation difficulties and inherent high variability in the underlying natural processes. In such cases, an alternative strategy to obtain risk reduction rather than through research efforts can be to develop technology and associated know-how that aims to reduce magnitude of the risk source or occurrences of the event/hazard/threats. It is to a certain extent possible to discuss and make suggestions about such

TABLE 4 Knowledge needs/R&D recommendations linked to key environmental risk components associated with deep-sea SMS mining.

Activity (α)	Risk source (RS′)	Event/ hazard/ threat (A′)	Consequence (C_A′) – 'direct impacts'			Knowledge needs/ R&D recommendations
from Table 2		Indicated probability of occurence before and (after) R&D mediated risk mitigation	Impact assumptions based on background knowledge	Uncertainty	Severity	
Site preparation – substrate removal	Translocated overburden	High (-> med./high)	Strong impact, limited areal magnitude	Natural community recovery potential	Ecological value/ vulnerability of buried biota	Baseline data to identify species. Natural recovery potential/connectivity of valuable/vulnerable benthic species/communities
Excavation of ore	Disrupted or removed seafloor	Very high (-> high)	Unavoidable mortality due to habitat removal	Natural habitat and community recovery potential	Ecological value/ vulnerability of removed habitats and destructed biota	Baseline data to identify species, habitats and ecological value. (Long term monitoring of actual natural recovery of habitats and biota by connectivity in mined areas)
	Suspended excavated ore particles	High (-> medium)	Particles cause significant metal toxicity and burial effects. Technology development and practice to limit particle spreading can be achieved. (Model indications): large possible variations in particle spreading	Particle spreading. Ecotoxicity and burial effects; destruction potential for species and ('direct') habitat damage	Community impacts in already classified vulnerable habitat forming (valuable/ vulnerable) species (e.g. sponges and corals, midwater fauna)	*Particle spreading: In-situ* studies of particle plume behavior. *Hydrodynamic models*: Standardization of applications and procedures to model excavated ore particles for risk assessment purposes. *Technology*: Develop solutions limiting particle resuspension and spreading. *Consequences:* Ore particles' burial effects in benthic species/communities and toxicity effects in benthic and pelagic species/communities. Identification of thresholds and protective set-aside areas (refuges). *Baselines:* Identification of species, incl. various ecological characteristics. Natural recovery potential/ connectivity of valuable/vulnerable benthic species/ communities. *Toxicity:* Examine and develop standard and new testing schemes and endpoints; metal toxicity in reference species and "bulk toxicity" in ecologically relevant benthic and midwater species. Examine the use of sub-lethal toxicity response methods (biomarkers) and mortality for 'direct impact' assessments and spatio-/temporal risk monitoring. Toxicity and threshold level determinations. *In-situ* verification of lab. experiments (offering also opportunities to connect with ecological field studies, e.g. benthic-pelagic coupling, as pre-requisite for studies of 'complex effects'). *Microbiomes:* Study impacts on sedimentary microbiomes in toxicity type studies and microbiomes within animals in impact studies (above). Studies to understand better the importance of microbiomes in deep-sea animals in inactive vent sites.
	Mining gear disturbances/ seafloor alterations	Medium/ Low (-> low)	Machinery may cause severe seabed structural damage. Altered seafloor/ water flows e.g. by inactive vent chimney removal known to be	Geological know-how and mining practice. Biota impacts	Altered habitats in affected seabed areas. Vulnerability and value of local biota	Improve geological know-how aiming to develop mining technology and good practice to avoid/ minimize seafloor structure alterations, water flows, or reactivated vent activity. Determination of minimum allowable distance of inactive to active vent fields for mining activity.

(Continued)

TABLE 4 Continued

Activity (α)	Risk source (RS')	Event/hazard/threat (A')	Consequence (C_A') – 'direct impacts'			Knowledge needs/ R&D recommendations
			possible. Expected frequency and biota impacts are uncertain.			
	Mining gear disturbances/ noise	Medium (-> low)	Deep-sea biota may experience detrimental noise impacts during the mining operation.	Noise impacts in deep-sea biota.	Potential long-term effects in valuable species vulnerable to noise disturbances.	Improve understanding of detrimental noise disturbances including spatial extent and determination of threshold levels. Develop technology to reduce to non-detrimental levels and minimize impacts.
Illuminating activities	Light at depth or surface	Medium (-> low)	Bioluminescence essential function in many deep-sea organisms. Importance of illumination in shallow waters well known and documented.	Understanding of deep-sea illumination impacts	Long-term vulnerability and value of biota affected by light disturbance	Improve understanding of bioluminescence in deep-sea (including midwater) organisms, particularly possible long-term impacts. Technology development to minimize the need for illumination in deep-sea mining.
Transport of ore from seafloor to surface	Translocated materials in lift system	Medium (-> med./low)	Mortality in local deep-sea (demersal) fauna. Mining particles, chemicals and microplastics exposure of shallow fauna.	Amounts of translocated deep-sea organisms and contaminants exposing shallow organisms. Associated ecotoxicity	Vulnerability and value of pelagic communities affected in shallow and deep waters	Technology development to minimize translocation of deep-sea organisms, materials and wear-and tear of riser pipeline. (Possible demand case by case to study toxicity of discharged contaminants and clarify impacts in pelagic communities affected in shallow or deep waters).
Transport of tailings/ return to sea floor	Returned fine sized tailing plumes	High (-> med./high)	Returned fine particles cause significant metal toxicity. Technology development and practice to limit fine particle spreading can be achieved. (Model indications): large possible variations in fine particle spreading.	Ecotoxicity, fine particle spreading	Community impacts in already classified vulnerable habitat forming (valuable) species (e.g. sponges and corals, midwater fauna).	The same research as recommended for suspended excavated ore particles applies to return tailings, however focused on finer particles (physical/ chemical fate and toxicity) and other affected species and communities, including in midwater and microbial, being pre-requisite for nutrient cycling and ecosystem functioning and other potentially 'complex effects' (e.g., biodiversity and ecosystem services). Standardization of hydrodynamic model applications and procedures for risk assessment purposes to estimate current mediated spreading and sedimentation of fine sized return plumes and of larvae (in support of connectivity and natural recovery processes). Overall aim is to develop know-how to minimize the spreading of return tailings.

developments at the present stage, hence, both development and research priorities are highlighted in the paper.

The suggested knowledge generation and R&D priorities are discussed in relation to the different mining activities (α) and their associated risk sources (RS') presented in Table 2 with the proposed risk framework providing a supporting structure.

While Table 2 summarizes important potential risks associated with the activities and risk sources (α, RS'), this information is expanded in Table 4 to indicate key aspects of background knowledge, uncertainty, and severity of 'direct impact' contributions to associated consequences (C_A').

Indications of event/hazard/threats (A') that the activities and risk sources (α, RS') are liable to cause are included in the discussion (below), and the likelihood of these occurring is indicated in Table 4 (3rd col.).

The potential 'direct impact' consequences (C_A') are listed briefly in Table 2, while other relevant aspects for knowledge improvement and R&D priorities are indicated in three consequence (C_A') columns

(4-6) in Table 4. These are related to key assumptions made in the existing background knowledge, to the strongest uncertainty factors, and to the assumed severity indicated in affected value, vulnerability and harmfulness.

The potential knowledge generation and identified R&D priorities are discussed for each activity in the following paragraphs (Sections 3.1.1-3.1.5) and summarized with recommendations in Table 4.

3.1.1 Activity: site preparation – substrate removal

It is expected that substrate removal to prepare a mining site (translocation of overburden) will be a necessary initial action in SMS mining projects. It is assumed to have a strong but spatially confined local impact, affecting the sites of substrate removal and substrate deposition in the mining area.

The area of substrate removal will later be affected by ore excavation, enhancing the removal impacts (Section 3.1.2). This leaves the ecological value of habitats and biota affected by the deposited overburden as the more important focus regarding severity of the overall site preparation impacts.

Epistemic uncertainties due to the present limited ecological knowledge about species and communities within future SMS mining sites elevates the environmental risk of site preparation activities. Studies on naturally disturbed sites (e.g. volcanic eruptions) have suggested that sites can recover in 2–4 years due to the presence of resilient fauna used to disruptions along the East Pacific Rise (Gollner et al., 2015; Marcus et al., 2009). Mullineaux et al. (2020) observed that the species community and composition of new colonist were still changing more than a decade after disruption and the successional stage still differed from the pre-eruption community. Moreover, in these often-disturbed areas it is difficult to establish a pre-disturbance baseline community. Even higher impact can be expected on (inactive) vent communities along the Mid-Atlantic Ridge that are not often exposed to disturbance and might respond much slower and are less resilient (Mullineaux et al., 2018). Currently, there is a lack of knowledge about the natural recovery potential of species along Mid-Atlantic Ridge vent sites as well as changes in environmental conditions that can influence succession.

Important research objectives can therefore be to generate baseline biodiversity data to identify species that are likely to be affected by site preparations overburden depositions, their occurrence, density, and functional traits, as well as their connectivity-based natural recovery potential. *In-situ* experiments with deployment of artificial substrates to estimate the recolonization potential and assess the composition and settlement potential of the regional species pool on these surfaces can be done in exploration or early phase of mining activity (Cuvelier et al., 2018). Adequate modelling methods and procedures must be established in relation to the connectivity assessments.

Possible active post mining recovery measures (mitigation) will be beyond the activities of actual mining covered herein and is thus outside the scope of the present R&D discussion. See Cuvelier et al. (2018) regarding possible mitigation and restoration actions.

3.1.2 Activity: excavation of ore

Deep-sea SMS mining will expectedly be carried out similar as open-pit mining on land, extracting minerals from the sea-floor surface. The method generates considerable amounts of ore particles potentially spreading with currents in plumes away from the mine site. Improved knowledge concerning the associated impacts is needed for environmental risk evaluations.

The SMS mining technology is at present moderately developed. A first-generation equipment was developed and built by Nautilus Minerals for the non-executed Solwara 1 seabed mining project (Steiner, 2009), however it did not include a particle plume control system. Development of solutions that are more environmentally protective by reducing particle spreading could be addressed. It can be part of the R&D objectives to shed light on the environmental risk reducing potential of such technology, know-how and practice developments and to provide guiding data on their optimization.

Several possible risk sources (RS') associated with the ore excavation activity (α) (Table 4) are treated separately in the following sections.

3.1.2.1 Risk source: disrupted or removed seafloor

Disruption or removal of seafloor is inevitable in the SMS excavation activities and thus the impacts and risks resemble those associated with removal of overburden (Section 3.1.1, above), however, with much larger physical impact. Habitat removal and mortality of affected biota can be assumed unavoidable, and the overall severity and risk will, in this case, be influenced mainly by the values of removed habitats and communities. Two types of habitats may be affected: the substrate itself (e.g., hard bottom, sponge spicule mats) and biogenic habitats created by structure-forming species protruding from the seafloor such as sponges or soft corals that provide habitat for many other species.

To be able to evaluate the impact and risk related to the removal of sea floor by the mining activity, baseline data must be generated to determine species likely to be affected, their habitats and ecological value. As for assessment related to the translocated overburden (Section 3.1.1) this can be done during exploration or early phase of mining activity.

The natural connectivity-based recovery potential of species may possibly reduce the impacts and risk. Connectivity pathways can be simulated or modelled when behavior of larvae and environmental conditions (e.g. near bottom circulation, topography) are known (Mitarai et al., 2016; Hilário et al., 2015; Yearsley et al., 2020). However, this aspect is in this case hardly predictable and assessable since the excavated seafloor and its habitats will be completely altered by the mining. Since it will be spatially limited, research on this aspect does not seem feasible. On the other hand, long term monitoring of mined SMS sites may yield interesting information about actual recolonization post-mining (Mullineaux et al., 2020).

3.1.2.2 Risk source: suspended excavated ore particles

3.1.2.2.1 Particle spreading

Suspension of excavated sediment and ore particles, plume-mediated transport by currents, and redeposition on the seafloor will contribute to the environmental risk due to metal toxicity when in suspension and by metal toxicity and smothering effects upon redeposition. It is indicated through modeling (Spearman et al., 2020; Mingotti and Woods, 2022) and measurements of benthic plumes from nodule mining (Gazis et al., 2025) that there can be large variations in particle spreading depending on the properties of the suspended matter (e.g., grain size, density, settling velocities, flocculation) and the environmental conditions, including current speed and direction, internal tides, and background turbidity. There is a need for *in-situ* studies of particle plume behavior after ore excavation technologies have been developed. These should serve as reference in test mining under future licenses.

3.1.2.2.2 Hydrodynamic models

The use of robust hydrodynamic models is essential for evaluating the environmental impacts of suspended particles generated during the excavation of SMS deposits. These models simulate how sediment-laden plumes, produced by mining activities, disperse in the marine environment, helping to predict the spatial extent, concentration, and duration of particle suspension. This is critical for assessing potential risks to benthic and pelagic ecosystems, including the smothering of habitats, reduced water quality, and impacts on filter-feeding organisms. While suitable hydrodynamic modeling tools already exist (e.g., Morato et al., 2022; Mingotti and Woods, 2022), their effective application requires careful consideration of site-specific oceanographic conditions such as currents, density and temperature gradients, and seafloor topography. To facilitate consistent and transparent impact and risk assessments across different projects or regions, the standardization of modeling protocols, including model input parameters, resolution, and validation techniques, is recommended. This would support stakeholders, regulatory bodies, and researchers in making more reliable comparisons and informed decisions about the environmental viability of SMS mining operations.

3.1.2.2.3 Technology

Presently, no technical solutions exist to limit the resuspension of excavated ore-particles, hence, the probability for this risk source (RS') leading to event/hazard/threats (A') related to such plume formation must be considered high (Table 4). It can be assumed, however, that environmental protective technological solutions can be developed to limit the resuspension and spreading of ore particles, suggesting that the high probability can be reduced to a medium or low level, depending on the effectiveness and functional stability of the solutions. The interest in such development will depend on the potential severity of consequences.

3.1.2.2.4 Consequences

There are presently large uncertainties related to the consequences of possible particle spreading, metal leaching from particles, ecotoxicity and burial effects. The severity of possible impacts on habitats and communities is largely unknown due to these uncertainties and those associated with the extent of spatial particle spreading.

To strengthen the knowledge of the consequences of modeled ore particle plumes, further research objectives should be to quantify the burial or suffocation effects from SMS particles in benthic species and communities and their toxicological effects in both benthic and pelagic species. It should be aimed at establishing threshold levels in relation to the flux of settling particles as well as to the dissolution of metals leached into the water phase before and after particle settlement. This may partly be carried out in laboratory studies (Wurz et al., 2024), but *in-situ* habitat studies will also be needed with a focus on spatial toxicity and burial impacts on benthic species as well as on seafloor and pelagic ecosystem functioning.

3.1.2.2.5 Baselines

Studies are needed to identify which species and communities need to be included in the risk assessment. Combined with modelled particle spreading and based on vulnerability and value assessment, the potentially affected benthic species/communities can be identified. Similar studies will then apply as in sections 3.1.1 and 3.1.2.1, however, it must be considered that these species may be others than those affected at the mining site. Consequently, separate studies of ecological characteristics of occurrence, density, functional traits, and connectivity/recovery potential needs to be conducted also for these species.

Species found to be obligately dependent on the inactive or extinct sulfide habitat should be investigated in terms of their specific ecosystem role, environmental adaptations, vulnerability and resilience to sediment plumes and habitat destruction. Such types of studies to obtain risk data are recommended and discussed by Van Dover (2014); Levin et al. (2016b) and Van Dover et al. (2020).

The above ecological baseline information will provide relevant impact and risk information, both in relation to 'direct impacts' and as pre-requisite knowledge for assessment of broader 'complex effects'. Additionally, this information can be used to identify and designate areas to be set-aside and protected from potential mining impacts (refuges). This is a comprehensive and precautionary approach for areas where the epistemic uncertainty is high (Cuvelier et al., 2018) as it currently is in potentially SMS mining influenced areas.

3.1.2.2.6 Toxicity

Toxicological data provide essential information about potential impacts for environmental risk assessment, being especially valuable in relation to 'direct impacts'. Such data of different endpoints exist for many commonly studied metals, however not for deep-sea organisms potentially impacted by SMS mining (Hauton et al., 2017). Exposure data exists for some shallow water species that may serve as proxy for deep-sea species, however conducted predominantly at standard temperature and pressure conditions, which can differ from high pressure and low temperature results (Mevenkamp et al., 2017; Brown et al., 2017). Most exposures are made with single metals in solution at single oxidation stage (Hauton et al., 2017). Such data can be useful, however not sufficient to predict potential impacts for risk assessments in different SMS mining influenced areas since mineral ores represent site-specific complex mixtures of metals (Hauton et al., 2017; Petersen et al., 2016; Belzunce-Segarra et al., 2015).

Hauton et al. (2017) proposes to assess the "bulk toxicity" of each mineral deposit to identify *a priori* the potential toxic risk of each mineral resource to be mined within a license area and for it to be determined under controlled, ecologically relevant conditions for a number of different locally relevant biological proxy organisms at their relevant life cycle stages. The physical state of the metal toxicant is considered important in the tests (*ibid.*). Incorporation of bioavailability concepts for assessing the chemical environmental risk and/or environment threshold values of metals and inorganic metal compounds should be considered (OECD, 2016). Such testing may provide relevant information for environmental risk assessment in SMS mining areas, however, there are also generic demands related to purpose of toxicity assessment which such testing approach do not necessarily meet.

Standardization of toxicity assessment that produces comparative quality of toxicity information will be needed for regulatory environmental management purposes. Standardized toxicity test methods are well established for other industrial activities with chemical discharges to the marine environment (e.g. OECD, n.d). One such set of methods is the Oslo and Paris Commissions (2006, 2012) toxicity tests, which include tests of growth inhibition of marine algae (*Skeletonema costatum*), acute toxicity of marine copepod (*Acartia tonsa*), and juvenile fish (*Scophtalamus maximus* or *Cyprinodon variegatus*) for water compartments, and a sediment reworker (*Corophium* sp) test for sinking substances. These water compartment test species can be expected to apply to discharges into shallow water of added chemicals (if this becomes relevant), however the representativity of the standardized tests and species for the deep-sea conditions is uncertain to similar effect as in the experiments with shallow water proxy species and standard temperature and pressure conditions discussed above.

Research is needed to clarify if species and test conditions in existing standard laboratory tests will provide relevant comparable data and contribute to inform risk assessment for deep-sea SMS mining operations. This must include standard exposure conditions and species applicability. It seems reasonable to consider that a combination of standard toxicity tests and other assessment methods must be used to obtain both mining site specific data and comparable data between sites.

Sub-lethal impacts of chronic exposure and behavioral avoidance by mobile organisms that may indicate toxic impacts in real time, are concepts that should be considered in a more holistic assessment of potential toxicity using the established weight of evidence (WOE) approach to quantify the toxic risk of deep-sea mining to biological species and communities (Hauton et al., 2017). Other aspects in such a combined approach are discussed in the following.

Laboratory exposures using crushed and chemically well-characterized SMS particles might be used to establish initial reference values of biological 'direct impacts' and accumulation effects potentially occurring in mining influenced areas. Longer term toxicity development both in benthic and midwater fauna can be results of metal bioaccumulation (Drazen et al., 2019). These reference studies can focus on organisms such as porifera, mussels, and protozoans, as models for impact assessment of SMS particles on species health and toxicity. Evaluation of bioaccumulation potential and types of toxicity can be done by analyzing tissue metal concentrations, biomarkers of sub-lethal effects and mortality rates in benthic and midwater organisms. However, method pre-studies in the deep-sea context will be necessary.

The availability of metals like copper, lead, and zinc in SMS deposits can trigger adverse biological effects, including oxidative stress and impairment of cell functioning (Martinez-Finlay and Aschner, 2011; Hauton et al., 2017). Oxidative stress is caused by an imbalance between reactive oxygen species production and antioxidant defenses, leading to cellular damage and altered physiological processes. Hence, sub-lethal biomarker responses relevant to cellular detoxification (e.g. metallothionine, catalase) may serve in testing of "bulk toxicity" for assessment of 'direct impacts' along with and related to mortality data. Biomarker responses are advantageous in that they might be measured in *in-situ* sampled organisms and be applied to serve as primary biological indicators of toxicity along plume gradients in down-current directions from mining sites. This can represent a valuable monitoring strategy to indicate the spatio-/temporal development of the risk during mining activities (see Section 3.2).

To assess severity of such toxicity in terms of 'direct impacts' will necessitate establishment of threshold levels based on dose-response (concentration-effect) data related to the above types of endpoints. This is not the same as thresholds for predicting broader ecological impacts (Levin et al., 2016b; Wurz et al., 2024) but may serve as pre-requisite to address 'complex effects' and further establishment of "serious harm" thresholds (sections 2.2.2 and 3.1.6).

Some verification of the toxicity data obtained in laboratory will be needed in the field. This could be achieved by conducting *in-situ* studies/experimentation with carefully selected exposures and with endpoints related to fitness, metal body burdens, and/or biomarkers. Such studies may also present connected opportunities to investigate ecological aspects (such as mechanisms of benthic-2pelagic coupling, e.g. in sponges) as pre-requisite to studies of 'complex effects'.

It can also be of interest in future mining projects to focus some exposure experiments with SMS particles on key benthic species observed in near-vent areas such as foundation species, VME indicators, or most common species. Ideally, these experiments should be carried out *in-situ* to reduce the effect of changing conditions (e.g., pressure). In addition, associated benthic and midwater fauna should be monitored to investigate the transfer of toxins into the food web (e.g. Bart et al., 2021).

3.1.2.2.7 Microbiomes

Further to studies of higher organisms, research is needed on microbial communities and their ecosystem functions. This is due to assumed high relevance and importance in these deep-sea environments (Orcutt et al., 2020) combined with the sparse existing ecological knowledge. Consequently, exposure studies addressing SMS particle impacts should in addition to higher organisms also be focused on microorganisms and include both sedimentary communities and internal microbiomes in higher deep-sea animals to obtain an improved understanding of their importance (Busch et al., 2022).

A recent study pinpointing the high primary production at inactive hydrothermal deposits, suggest that such mineral deposits are important to deep-sea carbon production (Achberger et al., 2024). Although, microbial ecological studies have been conducted at active vent locations at AMOR (Stokke et al., 2015; Steen et al., 2016; Dahle et al., 2018; Vulcano et al., 2022; Hribovšek et al., 2023), studies on inactive deposits, either exposed or buried in sediments at AMOR are missing. It is vital to conduct such studies to monitor and understand the impact of primary production on ecosystem services at such sites, and potentially how this is connected within the food web hierarchy in the Arctic Ocean. Any major changes on benthic fauna could impact the food supply of benthopelagic species and consequently alter the biodiversity of the pelagic communities (Christiansen et al., 2020).

3.1.2.3 Risk source: mining gear disturbances/seafloor alterations

Seabed mining machinery remains to be developed. Physical disturbances can be caused by vibrations from mining gear, leading potentially to structural seafloor alterations.

It is assumed that vent reactivation in inactive vent fields can potentially occur as result of drilling activities and chimney damages/removals. This will have severe consequences for the mining operation itself and will also affect the seafloor environment, e.g. by alterations in water flows and acidity, potentially posing destructive impacts on local habitats and biota (Kawagucci et al., 2013; Jamieson and Gartman, 2020).

The expected frequency of structural damages and potential impact severity are uncertain and need to be better known to understand their environmental risk. Hence, it should be prioritized research to improve geological know-how aiming to develop mining technology and good practice and avoid/minimize seafloor structure alterations, water flows, or reactivated vent activity. The gained knowledge should enable determination of how close inactive vent areas can be to active hydrothermal vent fields to allow mining activity. Technology protectiveness towards valuable habitats and benthic communities should be validated in *in-situ* experiments or at least demonstrated in test mining areas.

Seawater acidification due to weathering of SMS redeposits does not seem to represent a high environmental risk based on current knowledge, since actual acid production likely will be limited and not exceed the buffer capacity of seawater. This current knowledge is based on experimentally derived reaction rates and stoichiometrically calculated acid production (Bilenker et al., 2016).

3.1.2.4 Risk source: mining gear disturbances/noise

Mining gear disturbances will likely also include noise. Evidence based knowledge about sound perception in deep-sea animals is poor and the probable impacts of noise generation from deep-sea mining tools can currently not be predicted (Christiansen et al., 2020). Based on general knowledge of anthropogenic noise effects in the sea, instantaneous or continuous mining gear noises will potentially interfere with animal communication, predation, navigation, breeding processes, or cause damage to hearing organs (Stocker, 2002; Wall et al., 2014; Christiansen et al., 2020).

Key R&D objectivities should aim for better understanding of detrimental noise disturbances in deep-sea (including midwater) biota and to reduce noise to non-detrimental levels and minimize impacts. Use of bubble screens for noise mitigation used in shallow marine operations might be a possible development theme also in deep-sea operations (Zhu et al., 2023).

Since several deep-sea animals are dependent on sound and considering that noise impacts may also have long-term implication, the determination of threshold levels of disturbing noise is needed for the environmental risk management of deep-sea SMS mining. It is also important to investigate the spatial extent of noise pollution from mining gear due to far-reaching sound propagation with low loss of energy in the ocean (Stocker, 2002).

3.1.3 Activity: illuminating activities

Artificial light is a risk source both in the deep-sea during ore excavation and at the surface where processing will take place. It can be assumed that use of artificial light in deep-sea mining operations can have disturbing effects on bioluminescence, which serves essential functions in many deep-sea organisms (Haddock et al., 2010; Martini and Haddock, 2017). However, there are large unknowns in understanding the functions and roles of bioluminescence in deep-sea organisms. Uncertainty regarding sensitivity and long-term impacts in valuable species are important factors in the risk assessment (Christiansen et al., 2020).

R&D efforts should be made to better understand the potential long-term impacts that the use of light in SMS mining operations may cause in vulnerable/valuable deep-sea biota. The present high risk due to epistemic uncertainty can presumably be reduced by development of adequate technology development that minimizes the need for artificial lighting in the deep-sea (including midwaters).

Regarding possible artificial light effects at the surface, it can be assumed that sufficient basic knowledge already exists (e.g. related to oil and gas and ocean wind activities) to be able to assess the risk and associated risk measures (Ronconi et al., 2015; Leemans and Collier, 2022). Hence, no priority research objectives related to environmental risk are suggested herein, however, inclusion of studies focused on North Atlantic conditions may become required for SMS mining projects to be licensed in the area.

3.1.4 Activity: transport of ore from seafloor to surface

It is assumed that deep-sea organisms, chemical compounds and particles from wear and tear will be sucked in together with mined particles and seawater when ore is transported by the lift system (riser) to the sea surface.

Since impacts to local benthic organisms are already considered in association with the excavation activity (in Section 3.1.2), the focus is here mainly on other local demersal fauna. It can be assumed that mortality will occur in the organisms sucked into the riser caused by pressure changes and physical damage, and that ore particles, chemicals and microplastics brought to the surface and discharged may also expose and affect shallow living fauna.

The pelagic surface waters and its fauna can generally be expected less exposed to materials from the mining activity than benthic waters, seafloor and fauna. Still, there is much uncertainty related to the technology and practice, to the extent of mortality in organisms sucked into the riser, and to the toxicity of involved contaminants. Hence, at present the risk associated with transport of ore from seafloor to surface may be considered at a medium/high level, however, potentially reduceable towards a medium/low level by development of adequate environmental technology and practice.

Overall, it seems reasonable not to recommend specific research activities, but rather to prioritize development of technology aiming at minimizing the suction of deep-sea organisms, to minimize the wear and tear in lift systems, and to minimize the use and discharge/spreading of hazardous chemicals into surface waters.

The further assessment of the risk associated with the transport from seafloor to surface can case by case be based on toxicity testing (acute and chronic) of metal-containing ore particles and mining chemicals (if applicable) on relevant shallow community organisms in the licensed mining areas.

3.1.5 Activity: transport of tailings/return to seafloor

After recovering the ore at the sea surface, tailings will be transported and deposited near/at the sea floor. The environmental risk associated with this activity resembles the suspended excavated ore particles (in Section 3.1.2), however, the risk source will differ regarding particle size in the return tailings. These particles are expected to have smaller sizes (average diameters assumed around 2-4 μm) and larger surface areas. They are more susceptible to being spread by currents over extensive areas (Haalboom et al., 2020). The primary uncertainties include their ecotoxicity and their potential spreading over long distances. This dispersion could impact vulnerable and valuable benthic and pelagic species and communities beyond the immediate vicinity of the mine site.

At inactive sites, the background fauna being un-adapted to heavy-metal-rich and potentially toxic environments, as created by tailing plumes, may experience significant effects (Boschen et al., 2013). This may possibly affect organisms at all levels of the food chain (Weaver et al., 2019). Furthermore, the impacts may not be confined to a single depth band but develop into multiple plumes at different depths due to stratification and tidal regimes, and thus affect larger parts of the water column, including pelagic and benthic habitats (Klunder et al., 2020).

While most 'direct impacts' from seafloor mining can be expected to occur on the seafloor, the sediment plumes of the return transport to the seafloor has potential to become extensive in the water column. Therefore, environmental research and impact assessments should extend into the midwater realm (Drazen et al., 2019). Potential effects of seabed mining plumes on midwater ecosystems were discussed in a scientific workshop 2018 with outcome reported, including recommendations of both impact research and good practice to minimize such effects (*ibid*.).

Species and communities affected by fine particle return tailings can potentially differ from those nearer the mining site, hence all the same considerations and research priorities as recommended for suspended excavated ore particles (Section 3.1.2.2) will apply here but potentially focused on other affected species and communities.

Moreover, the presence of fine fraction particles can significantly alter microbial activity, crucial for nutrient cycling and ecosystem functioning. These particles can hinder microbial processes by introducing toxic metals that disrupt cellular functions, potentially leading to a reduction in microbial diversity and activity (Orcutt et al., 2011). The impairment of these processes can affect larger ecosystem functions, such as primary production and decomposition, ultimately leading to a loss of functional biodiversity.

Consequently, the potential risk is initially high and necessitates mitigation through adequate mining technology and practice. R&D efforts should parallel those recommended for suspended excavated ore particles but must specifically address the physical/chemical fate and toxicity of finer tailing particles. This includes evaluating impacts on microbiomes, both sedimentary and those mediated internally within affected animals, to ensure comprehensive risk assessment and management (see also Section 3.1.2.2).

Long-term environmental monitoring will be important in risk follow-up throughout duration of mining projects to support the environmental management. Understanding and mitigating the impacts of return particles is crucial for maintaining ecosystem resilience and preventing the loss of biodiversity and ecosystem services (see also Sections 3.1.2.2).

The required adequacy of hydrodynamic models and development/standardization of modeling procedures (in section 3.1.2, 3.1.2.2.2) is also needed to be able to simulate current mediated spreading and sedimentation of the finer tailing particles.

The modeling results must be verifiable in comparison to baseline *in-situ* measurements of environmental conditions including current speed, direction and turbidity to determine the effect of a plume. Also, modeling results must be configured to be verifiable against monitoring data to be obtained when matter is released at start of mining.

Another application of the hydrodynamic models in areas influenced by finer tailing particles will be to provide information to assess potential larval spreading in support of connectivity and natural recovery processes in potentially affected species and communities.

An overall aim related to the above is to develop know-how to reduce the environmental risk of return tailings by minimizing their spatial spreading.

3.1.6 R&D needs for 'complex effects'

Research results that will be gained to support assessments of 'direct impacts' recommended in sections 3.1.1-3.1.5 and Table 4 will expectedly also contribute to strengthen the background knowledge for 'complex effects'. The strength of this risk-relevant background information can be augmented by combining with pre-mining environmental baseline characterization (including mapping) and monitoring in early licensed areas for mining. However, due to the high complexity and unknown chain-of-events and effect pathways, additional research will in turn be needed to assess the risk of broader consequences ('complex effects'). In essence, the research needs for risk assessment related to 'complex effects' are similar to the research necessary to establish an operative knowledge base for "ecosystem-based" management.

Specification of these research needs in much detail is at present difficult, not the least because of unpredictability regarding event pathways, but some general guiding points are made in the following.

While recommended research related to 'direct impacts' are much focused on single species (or species assemblages), the research on 'complex effects' need to be more focused on ecological levels. Identification of species and associated fauna and linked ecological disturbances can serve as useful bridges between the studies related to 'direct impacts' and 'complex effects'.

Laboratory experiments can provide useful data, although weaknesses and uncertainty must also be considered due to the limited possibility of using actual deep-sea organisms and representing relevant biogeochemical interactions/event pathways in the laboratory. Enhanced strength of knowledge may be achieved by *in-situ* studies and experiments in the target areas, which could be made in combination with LIM or CaN food web interaction modeling (Soetaert and van Oevelen, 2009; Niquil et al., 2011; de Jonge et al., 2020; Planque and Mullon, 2020).

Other field studies and long-term observations are necessary to better understand and quantify the roles of temporal and spatial variations in environmental parameters (e.g., currents and temperature), organism responses to physical-chemical hazards, stress adaptation, natural community dynamics, trophic interactions, carbon and nutrient cycling, reproduction, population connectivity and recovery potential, aiming at making chains of event pathways and their consequences more predictable.

Regarding the severity of 'complex effects', several of the vulnerability criteria in Table 1 are closely linked to ecosystem functioning and services which are still poorly understood in inactive vent areas (Achberger et al., 2024; Levin et al., 2016b) and the deep-sea in general (La Bianca et al., 2023). The focus of the criteria has little attention on seafloor biogeochemistry, which is largely unknown in inactive SMS deposit habitats (Folkersen et al., 2018; Van Dover et al., 2020).

Studies characterizing the functional diversity and metabolism also of microbial communities are crucial to gain a sufficient understanding of possible risks to ecosystem functioning associated with potential 'complex effects' from deep-sea SMS mining. Possible small-scale test mining (Pickens et al., 2024) could offer opportunities for relevant environmental field studies. The complex microbial functioning and microbial/benthic macro/megafauna interactions in inactive hydrothermal vent areas (sedimentary and the microbiome) particularly need to be better understood to describe the risk of disrupted ecosystem functioning with its potential cascading biological community effects and disrupted ecosystem services (Orcutt et al., 2020; Van Dover et al., 2020; Achberger et al., 2024).

In sensitive areas with populations or assemblages of species with unpredictable recruitment (e.g., suspension-feeding invertebrates, structure-building benthic organisms), it will be crucial to obtain knowledge on metapopulation connectivity to understand vulnerability and potential of natural or artificial recovery of damaged populations in a mining area (Van Dover, 2014; Van Dover et al., 2014, 2020; Da Ros et al., 2019).

Regarding evaluation criteria related to 'complex effects', Clark et al. (2020) discusses elements that can form causal bases concerning possible cumulative impacts to ecosystem structure and function, including temporal accumulation, spatial accumulation, perturbation type, processes of accumulation, functional effects, and structural effects.

Emerging knowledge about events/hazards/threats, reflecting the development of mining technologies and practices for SMS mining in inactive vent areas, can lead to an improved knowledge base (Boschen et al., 2013) providing more specific characterizations of 'complex effects' than possible at present.

3.2 Environmental monitoring and management

In the ISA draft regulation, a purpose of the ERA is to contribute to define environmental monitoring plans for assessing the environmental consequences and risks (Section 1.3). Parameters to evaluate changes in the state of the environment or in the risk as operations progresses over time are sometimes referred to as "risk indicators" (RI; Figure 2; e.g. Sanni et al., 2017).

Too little data currently exists to propose adequate sets of RIs in relation to deep-sea SMS mining. While it is important for the future to identify and agree on common indicators, it can be expected initial needs for case-specific RIs to detect environmental changes associated with assessed risks in early mining operations (ISA, 2022b). Candidate RIs for this purpose can be parameters associated with or detecting changes within vulnerability/value criteria such as those in Table 1, or with time to emerging consequence and harmfulness criteria that are defined more specifically to SMS mining (Section 2.1.7).

To enhance management impact power in the future deep-sea SMS mining RIs, thresholds must be assigned. ISA currently elaborates on threshold levels related exploitation of polymetallic nodules regarding toxicity, turbidity and settling of resuspended sediments and underwater noise and light pollution. It is expected that thresholds will be similarly developed for polymetallic sulfide resources (ISA, 2024, 2025) to which the above risk relevant R&D to establish RIs for 'direct impacts' may provide relevant contributions.

Threshold determinations for broader 'complex effects' will presumably be more challenging to achieve, however, as a reasonable guiding starting point Levin et al. (2016b) suggest that key metrics to serve as threshold indicators regarding "serious harm" can be measures of biodiversity, abundance, habitat quality, population connectivity, heterogeneity levels, and community productivity.

Optical surveys and mapping are needed to determine the occurrence, extent and density of important structure-forming species and associated fauna to define their role as ecosystem engineers. Emerging methods such as environmental DNA (eDNA) metabarcoding, could contribute to rapid and more comprehensive habitat mapping efforts by detecting the presence of highly mobile fauna, small organisms or infauna which cannot be observed on images (Brandt et al., 2021; Gallego et al., 2024; Iguchi et al., 2024). Ongoing research using long-term deep-ocean sensing and observatories is also expected to yield crucial data on (natural) variability for this purpose (Danovaro et al., 2020; Matabos et al., 2022).

Monitoring and acceptance criteria related to threshold values forms important basis for decision making in the environmental management. The risk assessment adheres to this, as illustrated in Figure 2, although the management approach can be of different kinds. "Adaptive" and "ecosystem-based" management are two approaches that may have relevance for deep-sea SMS mining and contribute to sustainability. "Adaptive" management can allow for iterative adjustments for uncertainty from mining impacts, while "ecosystem-based" management enables a broad framework for ecosystem protection. "Adaptive" management can be considered most useful for mining companies, while the "ecosystem-based" management may be more relevant for government agencies focusing on the broader and longer-term developments that may extend beyond single mining operations. In this respect they may analogously be seen as most relevant for 'direct impacts' and 'complex effects', respectively, as they are defined herein.

In "adaptive" management, monitoring of activity (direct) impacts serve an essential purpose (Tunnicliffe et al., 2020; Clark et al., 2020; Norwegian Government, 2023). This is based on "learning by doing" mechanisms applied to the environmental management (Allen et al., 2011). It may be used to improve links between ERA results in the EIA to the monitoring strategies in the EMMP (Hyman et al., 2022a). It may allow for decision-making, adjustments and reversible management interventions in response to emerging information. Careful monitoring of possible impacts during the operations may be served by agreed RIs to be defined within the risk framework.

Such adaptive management may be suitable for the initial/early stages of a mining project (e.g., for management of 'direct impacts' and early management actions to avoid 'complex effects'), although it may meet regulatory challenges due to difficulties in conducting adaptive changes in environmental standards within a project duration and after its termination. Hence, it seems at least not adequate in relation to long-term impacts (Jaeckel, 2016) and it is not further discussed herein (see Hyman et al., 2022a alternatively).

"Ecosystem-based" management takes into account the full array of interactions within an ecosystem in assessments of 'complex effects', and it follows from the discussion herein that it cannot be expected possible to establish and make operative the basis for such an approach until after a substantial part of the knowledge gaps related to 'direct impacts' have been closed.

4 Summary

4.1 Environmental risk framework

A targeted policy and practice review is conducted to formulate an environmental risk framework for deep-sea SMS mining, and to apply it as basis for recommending R&D priorities to support adequate environmental risk-based management in future mining operations. The work is particularly aimed at the upcoming knowledge needs related to areas under Norwegian jurisdiction on the Arctic Mid-Ocean Ridge and is aligned both with the key elements of the draft ISA regulations of the International Seabed Authority and Norwegian government policies.

The presented environmental risk framework is formulated around a conceptual model that can be represented as Risk = $(C, U)_{\alpha\tau,\eta} = (RS, A, C_A, U)_{\alpha\tau,\eta}$, where C denotes the consequences of an activity α observed over a duration of time τ, and U denotes the uncertainties associated with C. C can be broken down into risk sources (RS), event/hazards/threats (A) and consequences (C_A) of the events, with the latter observed for a duration η after the occurrence of an event. The consequences can be made up of several 'direct impacts' or broader 'complex effects' related to the event/hazard/threats.

4.2 Risk descriptions

Initial descriptions of the risk are provided based on present expert opinions regarding SMS type of deep-sea mining activity. The descriptions are made within the presented framework structure and associated with its components by specified major risk sources (RS'), event/hazards/threats (A'), and potential consequences (C_A') of the events. The described risks have been judged by existing severity criteria (vulnerability, harmfulness, value). These decision-making factors related to "serious harm" will themselves need further development prior to safe commencement of deep-sea SMS mining due to associated uncertainties.

Uncertainty comes out as a key feature of the initially described environmental risk. This contributes to elevate it to an initially very high level, being an integrated component of the risk. The uncertainty is largely of epistemic nature due to lack of knowledge, which pinpoints why identifying the most important knowledge needs and recommend R&D priorities is a key target for the present review.

4.3 R&D recommendations

The very high initial risk level also implies that strengthening the weak knowledge base and developing environmentally favorable technological and practical solutions can serve to mitigate and reduce the present risk. Hence, both research and development activities are discussed.

The R&D discussions are made in relation to five core activities associated with SMS mining (site preparation, ore excavation, ore transport to surface, tailings return to seafloor, as well as different activities causing artificial lighting) and based on impact assumptions from background knowledge and associated uncertainty and severity factors. The knowledge needs and R&D recommendations are summarized in a table together with their associated risk components (Table 4).

The R&D recommendations are mainly made in relation to 'direct impacts' as the knowledge base will need further development regarding many of the herein recommended R&D results to define event- and impact pathways that may lead to the broader and longer term 'complex effects'. However, it can be expected that the results of the herein recommend R&D activities will clarify and improve predictability and other aspects of potential 'complex effects' for future management of deep-sea SMS mining. Some general considerations regarding research needs for 'complex effects' are made.

The results of the recommended R&D activities can also be expected to contribute important data to the establishment of parameters and methods for environmental monitoring. Especially for management within early stages of mining projects (which could be an "adaptive" management approach) it will be essential to monitor the risk development. This can be done by risk indicators that can be developed in close association with the herein recommended R&D. To determine threshold levels for these risk indicators will be a major research need that will tie the risk assessment and monitoring activities together, as they practically also must be in the environmental management and monitoring plans of future licenses.

For similar long-term management to avoid broader consequences (as based on "ecosystem-based" management approaches) including ecosystem interactions that can lead to 'complex effects', it is premature to identify much of the research basis for both risk and monitoring assessments until after a substantial part of the knowledge gaps related to 'direct impacts' have been closed.

4.4 Shortcomings and directions for improvement

Shortcomings for the use of the present proposed risk approach must be expected, and some possible improvement directions can be indicated:

A major present shortcoming is that "broad" consequences cannot be addressed adequately due to lack of knowledge about event pathways. This introduces uncertainties about which impacts that must be better investigated. This is the main reason why we have distinguished between 'direct impacts' and 'complex effects'. It will provide a direction for improvements aiming to clarify event pathways in the next steps, which will be helpful in defining exposures and population/community impacts. The risk assessment framework can be further refined based on such development.

Another present shortcoming is related to the above, considering that suggested improvements may imply development in the direction of "ecosystem-based" management, promoting sustainability, biodiversity and delivery of ecosystem services. Further improved ecosystem understanding in the SMS deep-sea mining areas is needed for advancing environmental impacts and risk towards integration into this kind of management scheme.

A third present shortcoming is the lack of standardization of methods for ecotoxicity assessments to provide key impact information for the risk assessment. Once such standardization and the difficulties related to testing of deep-sea mineral materials on deep-sea organisms are overcome, it will be possible to keep a comparative quality of toxicity information in the environmental assessments and ensure equal treatment of future mining operators and their projects.

The limited development of technology and practice for deep-sea SMS mining (or at least available information about such) is also a shortcoming for the present risk assessment framework which is based on activities, risk sources and events/hazards/threats. Such development will provide clarifications to further refine the present model.

The applied environmental risk framework and the outcome of recommended R&D activities can serve as tools for deep-sea SMS mining in Norway and hopefully provide input to harmonization and structure for ERA related to other seabed minerals and areas.

Author contributions

SS: Conceptualization, Writing – original draft, Visualization, Funding acquisition, Project administration, Methodology, Writing – review & editing, Supervision. PW: Writing – review & editing. RF: Methodology, Writing – review & editing, Visualization, Conceptualization. FM: Writing – review & editing. RS: Writing – review & editing. ME: Writing – review & editing. AG: Writing – review & editing. TB: Writing – review & editing. SD: Visualization, Writing – original draft. PR: Funding acquisition, Visualization, Resources, Project administration, Writing – review & editing, Supervision, Conceptualization.

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Conflict of interest

Author PW was employed by the company Geosed Ltd.

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

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