Ocean and Coastal Management 176 (2019) 24–39

Contents lists available at ScienceDirect

Ocean and Coastal Management

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

Ecological risk assessment for deep-sea mining

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ARTICLE INFO

Keywords:
Seabed mining
Expert survey
Polymetallic nodules
Polymetallic sulfides
Cobalt Crusts

ABSTRACT

Ecological risk assessment for deep-sea mining is challenging, given the data-poor state of knowledge of deep-sea ecosystem structure, process, and vulnerability. Polling and a scale-intensity-consequence approach (SICA) were used in an expert elicitation survey to rank risk sources and perceived vulnerabilities of habitats associated with seabed nodule, sulfide, and crust mineral resources. Experts identified benthic habitats associated with seabed minerals as most vulnerable to habitat removal with a high degree of certainty. Resource-associated benthic and pelagic habitats were also perceived to be at risk from plumes generated during mining activities, although there was not always consensus regarding vulnerabilities to specific risk sources from different types of plumes. Even for risk sources where habitat vulnerability measures were low, high uncertainties suggest that these risks may not yet be dismissed. Survey outcomes also underscore the need for risk assessment to progress from expert opinion with low certainty to data-rich and ecosystem-relevant scientific research assessments to yield much higher certainty. This would allow for design and deployment of effective precautionary and mitigation efforts in advance of commercial exploitation, and adaptive management strategies would allow for regulatory and guideline modifications in response to new knowledge and greater certainty.

1. Introduction

The deep seabed hosts mineral resources that are of interest to an emergent deep-sea mining industry (Hannington et al., 2011; Hein et al., 2013; Petersen et al., 2016). Much of the activity preparatory to commercial mining is taking place in international waters, including 29 exploration contracts (https://www.isa.org.jm/deep-seabed-minerals-contractors; accessed 1 October 2018) for mineral resources in Areas Beyond National Jurisdiction (ABNJ). These contracts were awarded by the International Seabed Authority (ISA), which has regulatory competency over all mineral resources in the ABNJ (Lodge, 2012). The ISA is also mandated under Article 145 of the United Nations Convention on the Law of the Sea (UNCLOS) to protect the flora and fauna of the marine environment from the impacts of mining activities (UNCLOS, 1982). Mining activities in the ABNJ will only be permitted once the exploitation regulations, including the environmental provisions, are approved by the ISA (Brown, 2018). Environmental management of deep-sea mining is a fledgling discipline (Jaeckel, 2015), with many unknowns relating to potential environmental risks and impacts of mining in the deep sea (Durden et al., 2018; Jones et al., 2018).

Ecological Risk Assessments (ERAs) may be used to prioritize ecosystem-based management objectives and investments in the appraisal, approval, and monitoring of activities with potential or realized impacts to ecosystems (Durden et al., 2018; Jones, 2001; Kaikkonen et al., 2018; OECD, 2006; Santos et al., 2018). In data-deficient areas, such as the deep sea, ecological unknowns (including but not limited to biodiversity, natural temporal and spatial variability, recovery rates, temporal and spatial scales of direct and indirect impacts, species distributions, connectivity) restrict the application of quantitative ERAs. Instead, ERAs for deep-sea activities may rely on expert opinion, literature review, and qualitative assessment of risk (Hobday et al., 2011; Kaikkonen et al., 2018; USEPA, 1992). Scale, Intensity, and Consequence Analyses (SICA) assess risks using expert opinion (Hobday et al., 2011), and a hierarchical risk assessment structure allows prioritization of higher risks and elimination of lower risks in the early stages of environmental impact assessment and mitigation planning (Clark et al., 2012; Hobday et al., 2011).

A SICA-based approach was used by Halpern et al. (2007) to rank

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https://doi.org/10.1016/j.ocecoaman.2019.04.014
Received 26 October 2018; Received in revised form 24 March 2019; Accepted 15 April 2019

Abbreviations

ABNJ	Areas Beyond National Jurisdiction
ANOVA	Analysis of Variance
DOSI	Deep-Ocean Stewardship Initiative
ERA	Ecological Risk Assessment
INDEEP	International Network for Scientific Investigations of Deep-Sea Ecosystems
ISA	International Seabed Authority
MIDAS	Managing Impacts of Deep-Sea Resource Exploration
POC	Particulate Organic Carbon
SICA	Scale-Intensity-Consequence Analysis
UNCLOS	United Nations Convention on the Law of the Sea
WOE	Weight of Evidence

the vulnerability of marine ecosystems (De Lange et al., 2010) to anthropogenic threats. A ‘generic’ deep-sea ecosystem was included in the Halpern et al. study, but the number of experts consulted was small (3 individuals) and, while deep-sea mining was one of the risks considered, there was no effort to identify and rank different types of risks that might arise from mining activities. Using the Halpern approach, we evaluated perceived risks associated with deep-sea mining, with a focus on three key mineral resource types—polymetallic nodules, polymetallic sulfides, cobalt crusts—and their associated habitats. To accomplish this, we sought expert opinion from deep-sea scientists using a survey approach i) to poll respondents on risks of greatest and least concern, ii) to poll respondents on biological consequences that were most or least likely, and iii) to assess perceived vulnerability of habitats associated with each mineral resource to 38 potential risk sources (not all of which were relevant to each habitat). Outcomes highlight potential priority areas for research investment and mitigation, as well as uncertainties and knowledge gaps.

2. Methods

2.1. On-line expert elicitation: survey design and deployment

2.1.1. Participant pool

Deep-sea experts who were engaged in the 3-year (2013–2016) European Commission-funded consortium focused on Managing Impacts of Deep-Sea Resource Exploration (MIDAS; ~120 individuals) were invited to participate in the survey. A broader invitation for expert participation was also distributed via the email list of the International Network for Scientific Investigations of Deep-Sea Ecosystems (INDEEP; > 1000 individuals). Respondents were asked to provide basic demographic information, including their stakeholder group, level of professional experience, and country.

2.1.2. Ethics statement

This research did not require Institutional Review Board approval. Participants were selected through an opt-in strategy and surveys did not include sensitive personal questions. Demographic information was analyzed in aggregate and opinions and personal information were kept confidential. Participants could opt to be acknowledged for their contribution.

2.1.3. Survey introductory material and framework

Substantive introductory material (“*Ecological Risk Assessment Survey for Deep-Sea Mining in the ABNJ: Explanatory Notes*”) was provided to participants (Supplementary File 1). This front material summarized the survey objectives, provided an overview of the survey and its structure, introduced a set of realistic mining scenarios for each mineral resource type to provide a standard frame of reference for respondents, outlined the survey process, and provided a preview of the question fields in the survey. In brief, the seabed mining process for nodules, sulfides, or crusts relies on one or more mining tools or vehicles that collects the resource and moves it to a riser pipe. Ore delivered from the seabed to the ship through a lifting system is dewatered on the ship; return water is released in the water column below the thermocline or near the seabed. In this mining scenario, the return water ‘plume’, also referred to as tailings, contains only fine particles (~10 μm), and there is no other shipboard processing. Nodules lie on the surface of abyssal sediments at depths of 5000 m in expansive two-dimensional distributions. Crusts occur as surficial layers up to 20 cm or more in thickness on hard substrata, especially on exposed seamounts and ridges. Sulfides occur as localized 3-dimensional deposits that may extend 30 or more meters in vertical dimension, and they may be associated with ‘active’ hydrothermal vents colonized by a high biomass of invertebrate taxa that host endosymbiotic bacteria (holobionts) dependent on sulfide-rich venting fluids, or with ‘inactive’ vents, where there is no evident fluid flow or holobionts. The mining tools to be used and the spatial and temporal scale of mining activities will differ among the mineral resource types.

The ecological risk assessment survey used in this study followed the habitat vulnerability survey framework of Halpern et al. (2007). Each respondent was thus guided through a nested survey structure based on mineral resource, habitat, risk category, risk source and habitat vulnerability measure, with the respondent providing a vulnerability score for five vulnerability measures and level of certainty for each potential risk source. Respondents were also given the option to answer "I don't know" or "not relevant" if they did not feel that providing a score was appropriate.

Habitats. For each mineral resource—nodules, sulfides, and crusts—a set of potentially vulnerable habitats was identified (Table 1). Five of these habitats—nodules, nodule sediment, active vent, inactive vent, and crust—are referred to herein as “key benthic habits” to indicate that these habitats could be directly impacted by mining activities. Respondents were given the opportunity to name additional habitats and to proceed with a vulnerability analysis for any such habitat.

Potential Risk Categories and Risk Sources. Five risk categories were defined based on the origin of the potential impact:

i. habitat alteration (including removal)
ii. other vehicle-generated impacts (light, noise, sound, species introductions)

Table 1
Habitats considered for each mineral resource type. ✓: indicates inclusion in the survey and subsequent statistical analyses; ✗: < 3 respondents for at least some vulnerability measure/risk category combinations, so not included in statistical analyses; NA: not applicable; —: zero responses.

	MINERAL RESOURCE		
	Manganese Nodules	Seafloor Massive Sulfides	Cobalt Crusts
“Key” Benthic Habitats			
nodules	✓	NA	NA
nodule sediment	✓	NA	NA
active vents	NA	✓	NA
inactive vents	NA	✗	NA
crust (hard substrata)	NA	NA	✓
Other Habitats			
other sediment	NA	✗	✗
other hard substrata	✗	✗	NA
serpentinite	NA	–	NA
benthopelagic	✗	–	✗
pelagic	✗	✗	–
coral gardens	NA	✗	✗
sponge grounds	NA	–	✗

Table 2

Risk categories and risk sources included in the survey, with selected references.

Risk Category	Risk Source	Selected References (see also citations within)
Habitat Alteration (Including Removal)	Habitat Removal	**Nodules**: (Bluhm, 1993; Glover and Smith, 2003; Jones et al., 2017; MIDAS (Managing Impacts of Deep Sea Resource Exploitation), 2016a,b; Miller et al., 2018; Oebius et al., 2001; Peukert et al., 2018; Ramirez-Llodra et al., 2011; SPC, 2013a) **Sulfides**: (Baker et al., 2010; Boschen et al., 2013; Coffey Natural Systems, 2008; Collins et al., 2013; Fukushima and Okamatsu, 2010; Glover and Smith, 2003; Gwyther, 2008; Halfar and Fujita, 2007; MIDAS (Managing Impacts of Deep Sea Resource Exploitation), 2016a,b; Miller et al., 2018; Narita et al., 2015; Ramirez-Llodra et al., 2011; SPC, 2013b; Steiner, 2009; Van Dover, 2014a, 2011b, 2011a) **Crusts**: (SPC, 2013c) **All**: (Ahnert and Borowski, 2000; DNV-GL, 2016; ECORYS, 2014; Gollner et al., 2017; Kaikkonen et al., 2018)
	Sediment Compaction	**Nodules**: (ECORYS, 2014; Glover and Smith, 2003; Gollner et al., 2017; Jumars, 1981; Oebius et al., 2001; Sharma, 2011; Smith, 1999; SPC, 2013a; Thiel, 2001; Weaver et al., 2018) **Sulfides**: (Fukushima and Okamatsu, 2010; SPC, 2013b) **Crusts**: (SPC, 2013c)
	Increased Homogeneity	**Nodules**: (Kaikkonen et al., 2018; MIDAS (Managing Impacts of Deep Sea Resource Exploitation), 2016a,b) **Sulfides**: (MIDAS (Managing Impacts of Deep Sea Resource Exploitation), 2016a,b; Miller et al., 2018)
	Increased Heterogeneity	**Nodules**: (MIDAS (Managing Impacts of Deep Sea Resource Exploitation), 2016a,b; Thiel, 2001) **Sulfides**: (MIDAS (Managing Impacts of Deep Sea Resource Exploitation), 2016a,b)
	Organic Enrichment	**Nodules**: (MIDAS (Managing Impacts of Deep Sea Resource Exploitation), 2016a,b; Sharma et al., 2001) **Sulfides**: (Fukushima and Okamatsu, 2010; MIDAS (Managing Impacts of Deep Sea Resource Exploitation), 2016a,b)
	Porewater Alterations	**Nodules**: (Gollner et al., 2017; MIDAS (Managing Impacts of Deep Sea Resource Exploitation), 2016a,b; Oebius et al., 2001; Thiel, 2001) **Sulfides**: (MIDAS (Managing Impacts of Deep Sea Resource Exploitation), 2016a,b)
	Hydrothermal Fluid Changes	**Sulfides**: (Gollner et al., 2017; MIDAS (Managing Impacts of Deep Sea Resource Exploitation), 2016a,b)
	Altered Hydrography	**Sulfides**: (Baker et al., 2010; Fukushima and Okamatsu, 2010; Gollner et al., 2017; Gwyther, 2008; Halfar and Fujita, 2007; MIDAS (Managing Impacts of Deep Sea Resource Exploitation), 2016a,b; Ramirez-Llodra et al., 2011; Van Dover, 2014b)
	Mineral Alteration (Hard Substrata)	**Sulfides**: (Halfar and Fujita, 2007; MIDAS (Managing Impacts of Deep Sea Resource Exploitation), 2016a,b) **All**: (Gollner et al., 2017)
Other Vehicle Impacts	Species Introductions	**Sulfides**: (Gwyther, 2008; Steiner, 2009; Van Dover, 2014b; Van Dover et al., 2007) **All**: (DNV-GL, 2016; ECORYS, 2014)
	Electromagnetic Radiation	**Sulfides**: (Steiner, 2009) **All**: (Gollner et al., 2017)
	Increased Light	**Nodules**: (SPC, 2013a) **Sulfides**: (Coffey Natural Systems, 2008; Fukushima and Okamatsu, 2010; Gwyther, 2008; Narita et al., 2015; SPC, 2013b) **Crusts**: (SPC, 2013c; Steiner, 2009) **All**: (DNV-GL, 2016; ECORYS, 2014; Gollner et al., 2017; Miller et al., 2018; Weaver et al., 2018)
	Increased Sound	**Nodules**: (SPC, 2013a) **Sulfides**: (Baker et al., 2010; Coffey Natural Systems, 2008; Fukushima and Okamatsu, 2010; Gena, 2013; Gwyther, 2008; SPC, 2013b; Steiner, 2009) **Crusts**: (SPC, 2013c) **All**: (DNV-GL, 2016; ECORYS, 2014; Gollner et al., 2017; Miller et al., 2018; Weaver et al., 2018)

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Table 2 (*continued*)

Risk Category	Risk Source	Selected References (see also citations within)
Vehicle-Generated Plume	Organism Burial	**Nodules**: (Glover and Smith, 2003; Jones et al., 2017; Jumars, 1981; MIDAS (Managing Impacts of Deep Sea Resource Exploitation), 2016a,b; Oebius et al., 2001; Ramirez-Llodra et al., 2011; Sharma et al., 2001; Smith, 1999; SPC, 2013a) **Sulfides**: (Baker et al., 2010; Boschen et al., 2013; Fukushima and Okamatsu, 2010; Gwyther, 2008; Narita et al., 2015; SPC, 2013b; Steiner, 2009) **Crusts**: (SPC, 2013c) **All**: (DNV-GL, 2016; ECORYS, 2014; Gollner et al., 2017; Miller et al., 2018; Weaver et al., 2018)
	Clogging of Suspension-Feeding Structures	**Nodules**: (ECORYS, 2014; Jumars, 1981; Peukert et al., 2018; Sharma et al., 2001; SPC, 2013a) **Sulfides**: (Baker et al., 2010; Fukushima and Okamatsu, 2010; Ramirez-Llodra et al., 2011; SPC, 2013b) **Crusts**: (Ahnert and Borowski, 2000; DNV-GL, 2016; SPC, 2013c)
	Alteration in Deposit-Feeding Behavior	**Nodules**: (Fukushima and Okamatsu, 2010; Glover and Smith, 2003; Jumars, 1981; SPC, 2013a) **All**: (Gollner et al., 2017)
	Plume Toxicity	**Nodules**: (Peukert et al., 2018; SPC, 2013a) **Sulfides**: (ECORYS, 2014; Halfar and Fujita, 2002; MIDAS (Managing Impacts of Deep Sea Resource Exploitation), 2016a,b; Narita et al., 2015) **Crusts**: (SPC, 2013c) **All**: (Ahnert and Borowski, 2000; DNV-GL, 2016; Gollner et al., 2017; Hauton et al., 2017)
	Alteration of Water Properties	**Nodules**: (Peukert et al., 2018; SPC, 2013a) **Sulfides**: (Halfar and Fujita, 2002; SPC, 2013b) **Crusts**: (SPC, 2013c)
	Sediment Particle Size Changes	**Nodules**: (ECORYS, 2014; Sharma et al., 2001; SPC, 2013a) **All**: (Gollner et al., 2017; Weaver et al., 2018)
	Masking of Bioluminescence	**Sulfides**: (Gwyther, 2008)
	Sunlight Attenuation	**All**: (Weaver et al., 2018)
Seabed Tailings Return Plume	Organism Burial	**Nodules**: (Jones et al., 2017; (MIDAS (Managing Impacts of Deep Sea Resource Exploitation), 2016a,b) **Sulfides**: (Fukushima and Okamatsu, 2010; Gwyther, 2008; Steiner, 2009)
	Clogging of Suspension-Feeding Structures	**Nodules**: (MIDAS (Managing Impacts of Deep Sea Resource Exploitation), 2016a,b) **Sulfides**: (Coffey Natural Systems, 2008; Fukushima and Okamatsu, 2010) **Crusts**: (Weaver et al., 2018) **All**: (Miller et al., 2018)
	Alteration of deposit-feeding activity	**Nodules**: (MIDAS (Managing Impacts of Deep Sea Resource Exploitation), 2016a,b)
	Plume Toxicity	**Nodules**: (MIDAS (Managing Impacts of Deep Sea Resource Exploitation), 2016a,b) **Sulfides**: (ECORYS, 2014; Gwyther, 2008; MIDAS (Managing Impacts of Deep Sea Resource Exploitation), 2016a,b; Narita et al., 2015; SPC, 2013b; Steiner, 2009) **Crusts**: (SPC, 2013c) **All**: (Hauton et al., 2017; Miller et al., 2018)
	Alteration of Water Properties	**Nodules**: (Peukert et al., 2018; SPC, 2013a) **Sulfides**: (SPC, 2013b; Steiner, 2009) **Crusts**: (SPC, 2013c) **All**: (Hauton et al., 2017; Van Dover et al., 2011)
	Masking of Bioluminescence	**All**: This Study
	Sunlight Attenuation	**Nodules**: (SPC, 2013a) **All**: (ECORYS, 2014)
	Increased POC Deposition	**Nodules**: (SPC, 2013a) **Crusts**: (SPC, 2013c)
	Nutrient Enrichment	**Nodules**: (Sharma et al., 2001) **Sulfides**: (Fukushima and Okamatsu, 2010) **All**: (DNV-GL, 2016; Weaver et al., 2018)

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Table 2 (*continued*)

Risk Category	Risk Source	Selected References (see also citations within)
Water Column Tailings Return Plume	Clogging of Suspension-Feeding Structures and Respiratory Organs	**Nodules**: (SPC, 2013a) **Sulfides**: (Fukushima and Okamatsu, 2010) **Crusts**: (SPC, 2013c) **All**: (ECORYS, 2014)
	Plume Toxicity	**Nodules**: (Halfar and Fujita, 2007) **Sulfides**: (Gwyther, 2008; MIDAS (Managing Impacts of Deep Sea Resource Exploitation), 2016a,b; SPC, 2013b) **Crusts**: (SPC, 2013c) **All**: (ECORYS, 2014; Hauton et al., 2017)
	Alteration of Water Properties	**Nodules**: (Amos and Roels, 1977; SPC, 2013a) **Sulfides**: (ECORYS, 2014; Fukushima and Okamatsu, 2010) **Crusts**: (SPC, 2013c) **All**: (DNV-GL, 2016; ECORYS, 2014; Miller et al., 2018)
	Masking of Bioluminescence Sunlight Attenuation	**Vents**: (Steiner, 2009) **Nodules**: (SPC, 2013a) **Sulfides**: (Fukushima and Okamatsu, 2010; SPC, 2013b) **Crusts**: (SPC, 2013c) **All**: (Ahnert and Borowski, 2000; ECORYS, 2014; Weaver et al., 2018)
	Increased POC Deposition	**Nodules**: (SPC, 2013a) **Crusts**: (SPC, 2013c)
	Nutrient Enrichment	**Nodules**: (Amos and Roels, 1977; MIDAS (Managing Impacts of Deep Sea Resource Exploitation), 2016a,b; Sharma et al., 2001; SPC, 2013a) **Sulfides**: (Fukushima and Okamatsu, 2010; Gwyther, 2008; Halfar and Fujita, 2007, 2002; MIDAS (Managing Impacts of Deep Sea Resource Exploitation), 2016a,b; SPC, 2013b) **Crusts**: (SPC, 2013c) **All**: (DNV-GL, 2016; ECORYS, 2014)
	Release of CO_2 in Surface Water	**Nodules**: (ECORYS, 2014) **All**: (Weaver et al., 2018)

iii. impacts from vehicle-generated sediment plumes
iv. tailings plumes returned near the seabed
v. tailings plumes returned mid-water.

Tailings in this context result from the shipboard dewatering process and consist of seawater with fine (< 10 µm) particles remaining after centrifugation (Coffey Natural Systems, 2008).

Within each risk category, potential risk sources were identified from published literature and amended in consultation with deep-sea experts (Table 2).

Survey Deployment. The online survey was designed using Qualtrics (Provo, Utah) software; a copy of the survey is included in Supplemental File 2. The survey was deployed from 4 July to 22 August 2016.

2.1.4. Expert elicitations

2.1.4.1. Expert identification of key risk sources and biological responses (polling approach). Respondents were asked to list in rank order up to 3 most important risk sources for any given habitat and to comment on the likelihood (not likely, low likelihood, medium likelihood, and high likelihood) that particular biological responses might occur in relation to each of these risk sources. Biological response options were: altered behaviors of organisms, modified trophic interactions, disruptions in connectivity, alternative ecological states, loss of standing stock, loss of biodiversity, loss of reproductive capacity, species extinction (at local, regional, and/or global scales), and increased or decreased primary or secondary productivity.

2.1.4.2. Habitat vulnerability measures (SICA approach). To assess the vulnerability of habitats to each risk source within the five risk categories, respondents were asked to rate each risk source according to five vulnerability measures:

i. scale of functional impact
ii. community resistance to disturbance
iii. recovery time following disturbance

Table 3
Scaling of habitat vulnerability measures. Additional details are provided in Supplementary File 1.

Habitat Vulnerability Measures	Quantitative Scoring	Descriptive Scoring
Scale of functional impact The primary functional level at which a risk source acts within a given habitat.	0	No impact
	1	Species (single or multiple)
	2	Single trophic level or functional group
	3	Multiple trophic levels or functional groups
	4	Entire community
Resistance to disturbance The average tendency for the species, trophic level(s), or entire community impacted by a risk source to remain in its 'natural' state and resist disturbance.	0	No impact
	1	High
	2	Medium
	3	Low
Recovery time following disturbance The average time required for the species, trophic level(s), or entire community impacted by a risk source to return to its 'natural' state.	0	No impact
	1	< 1 year
	2	1–10 years
	3	10–100 years
	4	> 100 years
Spatial scale of the risk source The average spatial scale at which a risk source impacts the habitat.	0	No impact
	1	< 1 km^2
	2	1–10 km^2
	3	10–100 km^2
	4	100–1000 km^2
	5	1000 to 10,000 km^2
	6	10,000 to 100,000 km^2
	7	> 100,000 km^2
Frequency of the risk source The average frequency of a risk source within a given habitat.	0	Never occurs
	1	Once
	2	Intermittent
	3	Continuous

iv. spatial scale of the risk source
v. frequency of the risk source.

A quantitative scale was set for each vulnerability measure (Table 3), adapted from Halpern et al. (2007). Respondents were also given the opportunity to report their degree of certainty for each risk source (zero, low, medium, high, or very high) within both the Polling and SICA Approach.

2.1.4.3. Cumulative impacts. Respondents were asked to assess their level of concern for cumulative impacts, should a mining event occur within the habitat they were considering. Cumulative impacts considered were: multiple mining events, ocean acidification, ocean warming, scientific research, tourism, marine debris/litter, commercial harvesting, bioprospecting, and cables/communication infrastructure.

2.2. Analyses

2.2.1. Expert identification of key risk sources and biological responses (polling approach)

A matrix was created for each habitat with risk sources as the rows and expert rankings of each risk source (#1 being highest ranked) as columns from the raw data. The number of experts in each row of the matrix was then weighted by a factor of 3 for a risk source assigned as #1, by a factor of 2 if assigned as #2, and by a factor of 1 if assigned as #3. Weighted scores were then summed for each risk. The resulting vector was used to identify the aggregate top 3 risk sources. Biological responses were examined for the aggregate top three risk sources for the key benthic habitats. For each of the aggregate top three risk sources, likelihood scores were averaged among participants who included the risk source in their top three. Average participant likelihood scores were then used to identify the most and least likely biological consequences for each risk source.

2.2.2. Habitat vulnerability measures (SICA approach)

2.2.2.1. Habitat comparisons. Owing to unequal and sometimes small numbers of respondents (3–18 individuals) as well as lack of normality and homogeneity of variance, non-parametric statistical analyses were used to test for significant differences among the four key benthic habitats for which there were 3 or more respondents for all risk category and vulnerability measure combinations (i.e., nodules, nodule sediments, active vents, crusts). While there were other habitats with 3 respondents, these all included several risk categories where one or more respondents did not assign scores for various vulnerability measures. A Kruskal-Wallis one-way Analysis of Variance (ANOVA) on ranks was performed with habitat as the variable to test for differences among habitats for each risk category. The small sample sizes and need for correction owing to multiple tests resulted in a lack of power in subsequent pairwise analyses. For this reason, when significant differences were found within the Kruskal-Wallis tests, mean values of the vulnerability scores were used to rank habitat vulnerabilities.

Grand mean scores for a habitat were obtained by averaging scores for all risk sources within a risk category as reported by each respondent and then averaging these risk category scores across all respondents for the habitat. Vulnerability measures left blank or answered with “don't know” or “not relevant” were not included in these averages. Average scores for risk categories often did not include all risk sources within the risk category. To obtain the range of scores for risk sources within a risk category for a habitat, vulnerability scores were first averaged across respondents for each risk source. The range within a risk category was then defined as the difference between the risk source with the highest and lowest habitat vulnerability scores.

2.2.2.2. Comparing key risk sources. To identify risk sources of greatest concern to participants for each habitat, vulnerability scores for each risk source were rescaled to a range of 0–4 (per Halpern et al., 2007). For example, ‘*spatial scale of the risk source*’ vulnerability scores, which ranged from 0 to 7, were multiplied by 4/7. Each of the five rescaled vulnerability scores for each risk source were then averaged across respondents for each vulnerability measure. These ‘combined’ habitat vulnerability scores were then averaged for the five vulnerability measures to yield an overall mean score for habitat vulnerability to a given risk source.

Table 4
Number of respondents for each habitat by mineral resource.

	Nodule Bed	Nodule Sediment	Hard Substrata	Bentho-pelagic	Pelagic
Polymetallic Nodules					
Scientist	13	9	3	2	2
Industry	1	1			
ISA Contractor	2	1			
Consultant	1				
Government	1				
TOTAL	18	11	3	2	2

	Active Vents	Inactive Vents	Hard Substrata	Coral Gardens	Sediment	Pelagic
Polymetallic Sulfides						
Scientist	5	2	3	1	1	1
Industry	1	1				
ISA Contractor	1					
Consultant						
Government						
TOTAL	7	3	3	1	1	1

	Crust	Bentho-pelagic	Coral Gardens	Sponge Grounds	Sediment
Polymetallic Crusts					
Scientist	3	1	1	1	1
Industry					
ISA Contractor		1			
Consultant					
Government					
TOTAL	3	2	1	1	1

3. Results

3.1. Respondent demographics

Thirty-three respondents (mostly deep-sea ecologists) completed at least a portion of the environmental risk assessment survey for one or more habitats associated with deep-sea mineral resources (Supplementary File 3: Tables S1, S2). Experts considering the nodule habitat were best represented (18 individuals), followed by the nodule sediment habitat (11 individuals), active vent habitat (7 individuals), and crust habitat (3 individuals; Table 4). The inactive vent habitat and hard substratum habitat associated with nodule and sulfide resources each had 3 respondents. All other habitats had 2 or fewer respondents (Table 4). Twenty individuals completed the survey for 1 habitat, 6 completed surveys for 2 habitats, 3 completed surveys for 3 habitats, 2 completed surveys for 4 habitats, 1 completed surveys for 5 habitats, and 1 completed surveys for 7 habitats (not shown). Most respondents were scientists (27 individuals). Nearly half of all respondents were established scientists with more than 7 years of experience, 10 were early-career scientists, post-docs, or graduate students; seven respondents did not define their experience. In addition to scientists, there was representation from industry, the ISA, consultants, and government (Supplementary File 3: Table S2). Two-thirds of respondents (22 individuals) self-identified as associates of the MIDAS consortium and most survey participants belonged to the professional associations INDEEP, the Deep-Ocean Stewardship Initiative (DOSI), the Deep-Sea Biological Society, and/or VentBase (not shown).

The three most represented countries were Germany, the United Kingdom, and the USA, with six respondents each. There were four respondents from Belgium. The remaining 11 respondents were from 10 different countries, with Asia and Oceania represented by one respondent each (Supplementary File 3: Table S2). South America and Africa were not represented.

3.2. Habitats considered

The survey included opportunities for participants to consider 20 habitats, but only four habitats had 3 or more respondents assign scores to all risk categories for all vulnerability measures (Table 1): nodules, nodule sediment, active vents, and cobalt crusts. Pelagic environments, coral gardens, sponge grounds, and ‘other’ hard substrata (e.g., basalt on mid-ocean ridges) had low response rates, with fewer than three respondents for some or all combinations of vulnerability measures and risk categories (Table 1). The habitats that could be directly impacted by mineral exploitation—nodules, nodule sediments, active vents, inactive vents, and cobalt crusts—are referred to herein as ‘key benthic habitats’. In its Mining Code for exploration, the ISA calls for protection of “vulnerable marine ecosystems, in particular, hydrothermal vents …” from serious harm (International Seabed Authority, 2010). Active hydrothermal vents are included in this survey because at present, no authorized regulation or guideline prohibits exploitation of sulfides at active vents in the seabed area under the jurisdiction of the ISA. No respondents assessed risks of mining to serpentinite systems, sponge grounds, and benthopelagic environments associated with polymetallic sulfides, or pelagic environments overlying cobalt crusts (Table 1). Respondents were given the opportunity to identify other important habitats associated with a given mineral resource, but no additional habitats were offered.

3.3. Expert identification of top risk sources and biological responses (polling approach)

When invited to list risk sources of greatest concern, habitat removal was the top-ranked risk source identified for all benthic habitats except coral gardens associated with sulfide resources, where habitat removal was ranked third after plume effects (Table 5). Risks to deep-sea benthic habitats from sediment plumes (including, but not limited to burial, clogging of suspension-feeding structures and respiratory organs, toxicity; in addition, there were some generic responses, e.g., ‘vehicle-generated’ plumes) were also among the top risk sources volunteered by experts. For benthopelagic habitats, risks associated with vehicle-generated plumes, habitat removal, and return plumes released near the seabed were top-ranked risk sources. For pelagic habitats, risks associated with return plumes and plume-associated risks relating to changes in water quality were top ranked.

The most likely biological consequences of expert-identified risk sources to key benthic habitats (Table 6) were wide ranging, including but not limited to effects on reproductive capacity, trophic ecology, community structure, biodiversity, behavior, and population connectivity. Biological consequences of least concern often included global and regional species extinctions and increased secondary production. In some instances, responses could be conflicting. For example, for plume toxicity in inactive vent habitats, there were ties between most likely consequences of increased and decreased primary and secondary production.

3.4. Habitat vulnerability measures (SICA approach)

3.4.1. Habitat vulnerabilities by risk category for key benthic habitats

3.4.1.1. Habitat alteration (including removal). There were significant differences among key benthic habitats in perceived vulnerabilities to functional impacts and spatial scales of impacts associated with habitat alteration (Table 7; refer also to Fig. 1, **red bars**). Habitat alteration was perceived to have a functional impact at multiple trophic levels or the entire community in nodule and vent habitats, but only a single trophic level in crust habitat (Fig. 1A), with active vents ranked as most vulnerable in aggregate for risk sources within this risk category. Community resistance to habitat alteration was perceived to be low for nodule and vent habitats, with a large range of perceptions for inactive vent and crust habitats, from low to high or very high resistance (Fig. 1B). Recovery following mining was perceived to take decades or longer for nodule and vent habitats that were altered or removed by mining activities; a large range of recovery times (from no impact, i.e., zero recovery time, to greater than a century) for crusts was elicited from experts (Fig. 1C). Expert perception was that spatial scales of impact were on the order of 1000's of km^2 in nodule habitats compared to spatial scales of $10\,km^2$ for crusts and $< 10\,km^2$ for vents

Table 5
Top 3 risk sources by habitat, ranked by weighted scores of participants in aggregate; n = number of respondents.

	Risk Source	n	Weighted Score
Key Benthic Habitats			
Nodules	Habitat removal	14	42
	Burial from plumes	8	13
	Vehicle-generated plume	3	6
Nodule Sediments	Habitat removal	8	24
	Burial from plumes	5	7
	Sediment compaction/altered sediment biogeochemistry	3	6
Active Vents	Habitat removal	6	17
	Hydrothermal fluid changes	2	4
	Plume toxicity	3	4
Inactive Vents	Habitat removal	3	8
	Plume toxicity	2	4
	Habitat alteration	1	2
Crusts	Habitat removal	3	9
	Vehicle-generated plume	2	4
	Clogging of suspension-feeding and respiratory structures	1	2
Other Benthic Habitats			
Sediments: Sulfide Resource	Habitat removal	1	3
	Vehicle-generated plume	1	2
	Return plume	1	1
Sediments: Crust Resource	Habitat removal	1	3
	Vehicle-generated plume	1	2
	Sediment compaction	1	1
Other Hard Substrata: Nodule Resource	Habitat removal	2	4
	Burial from return plume	1	3
	Burial from vehicle-generated plume	1	2
Other Hard Substrata: Sulfide Resource	Habitat removal	2	6
	Plume toxicity	2	4
	Vehicle-generated plume	1	3
Coral Gardens: Sulfide Resource	Return plume	1	3
	Vehicle-generated plume	1	2
	Habitat removal	1	1
Coral Gardens: Crust Resource	Habitat removal	1	3
	Vehicle-generated plume	1	2
	Plume toxicity	1	1
Sponge Grounds: Crust Resource	Habitat removal	1	3
	Vehicle-generated plume	1	2
	Return plume released near the seabed	1	1
Pelagic Habitats			
Benthopelagic: Nodule Resource	Vehicle-generated plume	2	4
	Habitat removal	1	3
	Changes in sediment porewater geochemistry	1	2
Benthopelagic: Crust Resource	Habitat removal	1	3
	Vehicle-generated plume	1	3
	Habitat alteration/return plume released near seabed	1	2
Pelagic: Nodule Resource	Changes in dissolved O_2 and temperature	1	3
	Changes in CO_2 and pH	1	2
	Increased turbidity	1	1
Pelagic: Sulfide Resource	Return plume	1	3

Table 6

Biological consequences of greatest and least concern for the top three risk sources perceived to affect key benthic habitats. Superscripts denote rank order (1 = greatest/least concern) and indicate ties.

Habitat	Risk Source	Biological Consequences of Greatest Concern	Biological Consequences of Least Concern
Nodules	Habitat Removal	Loss of Reproductive Capacity^{1} Trophic Modifications^{2} Altered Community Structure^{2} Altered Organism Behavior^{2} Local Extinction^{2} Loss of Standing Stock^{2}	Global Extinction^{1} Increased Secondary Production^{2} Regional Extinction^{3}
	Plume Burial	Decreased Secondary Production^{1} Loss of Reproductive Capacity^{2} Trophic Modifications^{2} Altered Community Structure^{2} Altered Organism Behavior^{2} Disruptions in Connectivity^{2}	Increased Secondary Production^{1} Biodiversity Loss^{2} Loss of Standing Stock^{2} Regional Extinction^{2} Global Extinction^{2}
	Vehicle-Generated Plume	Disruptions in Connectivity^{1} Increased Secondary Production^{2} Altered Organism Behavior^{3}	Biodiversity Loss^{1} Regional Extinction^{2} Loss of Standing Stock^{3}
Nodule Sediments	Habitat Removal	Altered Community Structure^{1} Decreased Secondary Production^{2} Trophic Modifications^{2} Loss of Standing Stock^{2}	Increased Secondary Production^{1} Global Extinction^{2} Regional Extinction^{3}
	Plume Burial	Reproduction Loss^{1} Loss of Standing Stock^{2} Biodiversity Loss^{2} Connectivity Disruptions^{2} Regional Extinction^{2}	Increased Secondary Production^{1} Global Extinction^{2} Decreased Secondary Production^{3} Trophic Modifications^{3}
	Sediment Compaction	Reproduction Loss^{1} Connectivity Disruptions^{2} Altered Community Structure^{2} Decreased Secondary Production^{2} Trophic Modifications^{2}	Increased Secondary Production^{1} Local Extinction^{2} Regional Extinction^{3}
Active Vents	Habitat Removal	Biodiversity Loss^{1} Loss of Reproductive Capacity^{2} Trophic Modifications^{3} Altered Organism Behavior^{3} Connectivity Disruptions^{3} Local Extinction^{3} Loss of Standing Stock^{3}	Regional Extinction^{1} Global Extinction^{2} Increased Primary Production^{3} Increased Secondary Production^{3}
	Hydrothermal Fluid Changes	Biodiversity Loss^{1} Loss of Reproductive Capacity^{2} Connectivity Disruptions^{3}	Global Extinction^{1} Regional Extinction^{2} Trophic Modifications^{3} Local Extinction^{3} Altered Organism Behavior^{3} Loss of Standing Stock^{3} Decreased Primary Production^{3} Decreased Secondary Production^{3} Altered Community Structure^{3}
	Plume Toxicity	Trophic Modifications^{1} Local Extinction^{1} Decreased Primary Production^{1} Decreased Secondary Production^{1} Regional Extinction^{1} Increased Primary Production^{1} Increased Secondary Production^{1}	Reproduction Loss^{1} Global Extinction^{2} Altered Organism Behavior^{3} Loss of Standing Stock^{3} Altered Community Structure^{3} Biodiversity Loss^{3} Connectivity Disruptions^{3}
Inactive Vents	Habitat Removal	Increased Primary Production^{1} Increased Secondary Production^{1} Decreased Secondary Production^{1} Trophic Modifications^{1} Altered Organism Behavior^{1} Altered Community Structure^{1} Loss of Reproductive Capacity^{1}	Global Extinction^{1} Regional Extinction^{2} Loss of Standing Stock^{2} Local Extinction^{2}
	Plume Toxicity	Increased Primary Production^{1} Increased Secondary Production^{1} Decreased Secondary Production^{1} Decreased Primary Production^{1}	Biodiversity Loss^{1} Connectivity Disruptions^{1} Local Extinction^{1} Loss of Standing Stock^{1}
	Habitat Alteration	No Responses	No Responses

(*continued on next page*)

Table 6 (*continued*)

Habitat	Risk Source	Biological Consequences of Greatest Concern	Biological Consequences of Least Concern
Crust	Habitat Removal	Increased Secondary Production[1] Decreased Secondary Production[1] Connectivity Disruption[3] Loss of Reproduction[3]	Global Extinction[1] Regional Extinction[2] Altered Organism Behavior[3]
	Clogging of Filter Feeders	Connectivity Disruption[1] Loss of Reproduction[1] Altered Organism Behavior[2]	Regional Extinction[1] Loss of Standing Stock[2] Trophic Modifications[2] Altered Community Structure[2] Loss of Biodiversity[2] Local Extinction[2]
	Vehicle-Generated Plume	Altered Organism Behavior[1] Loss of Standing Stock[1] Connectivity Disruption[3] Trophic Modifications[3] Altered Community Structure[3] Local Extinction[3]	Global Extinction[1] Regional Extinction[1] Decreased Secondary Production[3] Loss of Reproduction[3] Loss of Biodiversity[3]

(Fig. 1D). The frequency of impacts from habitat alteration was perceived to be intermittent for all habitats (Fig. 1E). Respondents commented that impacts of risks associated with habitat alteration would be similar to impacts from habitat removal. They also noted that sediment compaction would depend on the type of equipment used.

3.4.1.2. Vehicle/installation impacts (other than habitat alteration). There were no significant differences in expert opinion regarding other vehicle impacts for any vulnerability measure (Table 7; refer also to Fig. 1, **orange bars**). 'Other' vehicle impacts were perceived to impact a single species in crust and inactive vent habitats and single or multiple trophic levels in all other habitats (Fig. 1A). Community resistance to 'other' vehicle impacts was perceived to be medium in all habitats, but with wide-ranging opinions (from low to very high resistance) for crust habitats (Fig. 1B). Recovery time following 'other' vehicle impacts was perceived to take < 1–10 years for all habitats (Fig. 1C). Spatial scales of impact were perceived to be on the order of 10's of km^2 in nodule beds and < 1–10 km^2 for vent and crust habitats (Fig. 1D). The frequency of vehicle impacts was generally perceived to be intermittent for all habitats (Fig. 1E). Comments from respondents noted that all risks associated with direct impacts from vehicles/installations other than habitat alteration would have limited, short-lived effects that would primarily affect mobile, pelagic animals.

3.4.1.3. Vehicle-generated plume. There were significant differences among habitats in the perceived functional impacts on communities and the spatial scale of impacts from a vehicle-generated plume (Table 7; refer also to Fig. 1, **green bars**). Vehicle-generated plumes were perceived to have functional impacts at single or multiple trophic levels in nodule and vent habitats, but only at the single species level in crust habitats (Fig. 1A). Resistance to vehicle-generated plumes was perceived on average to be medium to low in nodule habitats and higher in vent and crust habitats, but with wide-ranging opinions (from low to very high resistance) for inactive vents (Fig. 1B). Recovery time from vehicle-generated plumes was perceived to take tens of years in nodule habitats, but 1–10 years for vent and crust habitats (Fig. 1C). Spatial scales of impact for vehicle-generated plumes were perceived likely to be on the order of 100's of km^2 in nodule habitats, 10's of km^2 for crusts, and less than 10 km^2 for vent habitats (Fig. 1D). The frequency of impacts from a vehicle-generated plume was perceived to be intermittent for all habitats except inactive vents, where experts suggest the impact might be more continuous than intermittent (Fig. 1E).

3.4.1.4. Tailings return plumes. There was a significant difference among habitats in the perceived functional impact of a return plume released near the seabed, but there were no significant differences among habitats detected for a return plume released mid-water (Table 7; refer also to Fig. 1**, dark- and light-blue bars**). Return plumes were perceived on average to have a functional impact at the level of single or multiple trophic levels in nodule and vent habitats, but at the single species level in crust habitats (Fig. 1A). Benthic communities were perceived to have medium resistance to seabed return plumes and higher resistance to water-column return plumes (Fig. 1B). Expert perception was that recovery time following a seabed return plume in nodule sediment habitats would be 10 years or more; recovery following return plumes located at the seabed and in the water column in the other habitats might take fewer than 10 years (Fig. 1C). Return plumes were perceived to impact 100's of km^2 in nodule beds, but only 10's of km^2 in crust habitats and 1 km^2 in vent habitats (Fig. 1D). The frequency of impacts from return plumes was perceived to be intermittent for all benthic habitats, but with wide-ranging opinions (from never to continuous) for inactive vents (Fig. 1E).

In their commentaries, some respondents expressed doubt about vulnerabilities to risk sources associated with plumes, since the plumes were assumed to overlie mined, and thus already heavily impacted, areas. Some respondents commented that return plumes would have little impact on seafloor habitats owing to dilution and rapid return to

Table 7

Habitat vulnerability scores by risk category compared among 4 key benthic habitats. Kruskal-Wallis ANOVA; N: Nodule, NS: Nodule Sediment, AV: Active Vents, C: Crust; there were insufficient responses to include inactive vents in this analysis. For $p < 0.05$, the rank order of habitats by grand means (high to low vulnerability) is provided in parentheses.

Risk Category	Habitat Vulnerability Measures: * p < 0.05; ns: not significant; (habitat rank order)				
	Functional Impact	Resistance	Recovery Time	Spatial Scale	Frequency
Habitat Alteration	* **(AV > N > NS > C)**	ns	ns	* **(N > NS > C > AV)**	ns
Other Vehicle Impacts	ns	ns	ns	ns	ns
Vehicle Plume	* **(NS > N > AV > C)**	ns	ns	* **(N > NS > C > AV)**	ns
Seabed Plume	* **(NS > N > AV > C)**	ns	ns	ns	ns
Column Plume	ns	ns	ns	ns	ns

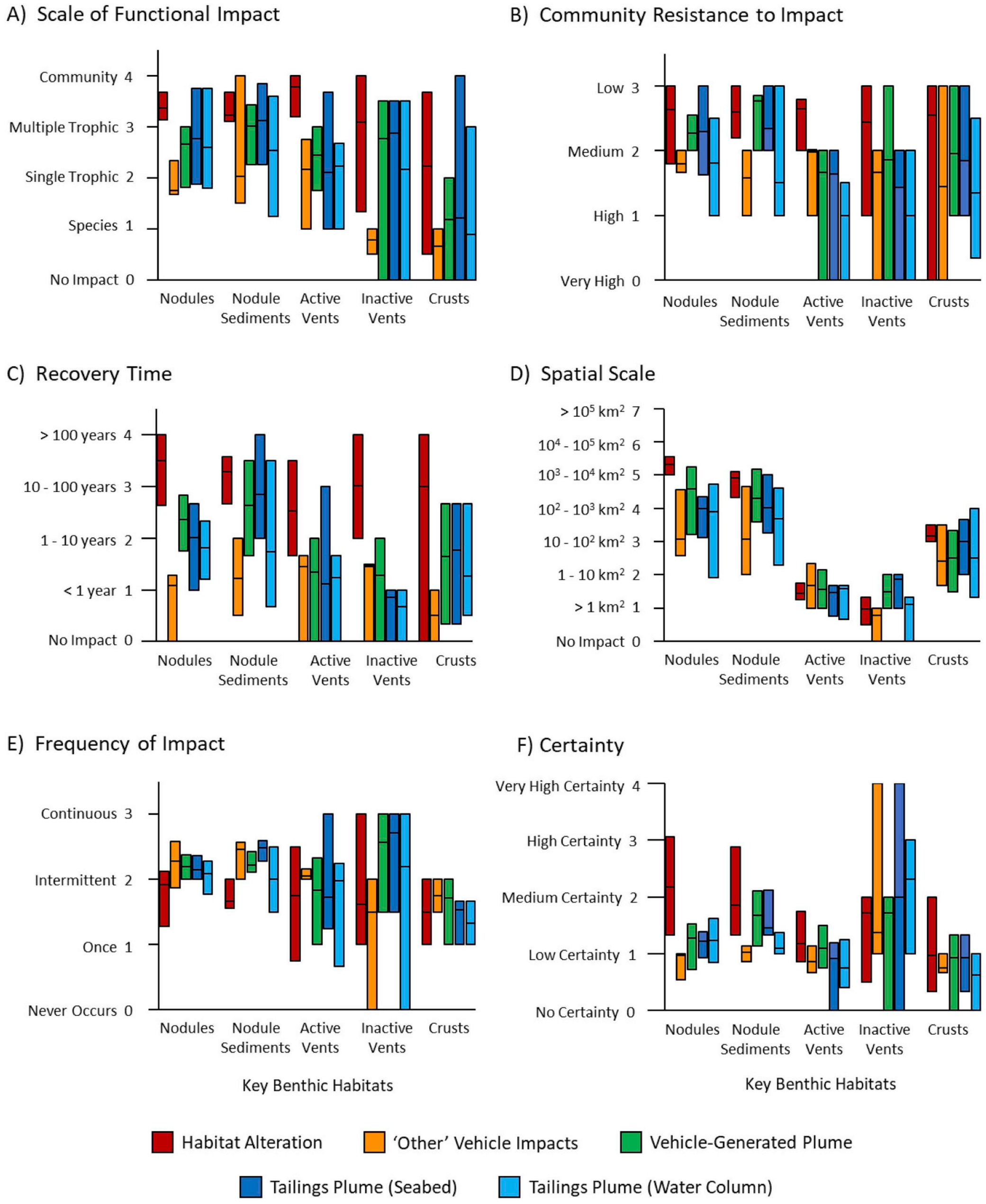

Fig. 1. Vulnerability of key benthic habitats to deep-sea mining by risk category. A–E: Habitat vulnerability measures, F: Certainty of risk-source effects. Values for each risk category represent grand means (horizontal line) and ranges (bars).

ambient conditions, low organic content in deep water, and filtration of mineral-processing wastewater before return. Additional comments were that plumes might shift and thus not be at any one place during the life of a mine, and that shifting plumes could move back into areas previously impacted, increasing the frequency of impacts. Some respondents noted that vehicle-generated plumes may impact suspension- and deposit-feeders, but because return plumes were assumed to have little organic matter and only fine particles, others thought that suspension- and deposit-feeding organisms would not be vulnerable. Respondents noted the need for more data concerning toxicological risks associated with all plumes.

3.4.1.5. Certainty of expert opinion. Overall, respondents reported a large degree of uncertainty in their scoring of vulnerability measures (Fig. 1F). The greatest certainty (medium to high) regarding vulnerability to habitat alteration was for nodule habitats and inactive vent habitats (Fig. 1F**, red bars**). There was very low certainty about the vulnerability of seabed habitats to other vehicle impacts (Fig. 1F, **orange bars**) and low to medium certainty regarding the vulnerability of seabed habitats to vehicle-generated plumes or return plumes (Fig. 1F, **green, dark- and light-blue bars**), but with wide-ranging opinions (from no certainty to very high certainty) for seabed return plumes at inactive vents.

Uncertainty was also measured by the number of vulnerability measure scores left blank or scored as 'don't know' for a given habitat (Fig. 2A–C) or risk category (Fig. 2D). For nodule and vent habitats, approximately 50% of all possible vulnerability scores were blank or answered 'don't know'; this percentage was 25% for crust habitats. For all habitats and risk categories where there was more than 1 respondent, the combined blank and 'don't know' responses accounted for at least 25% of all responses and greater than 50% for hard substrata and pelagic habitats (nodule and sulfide resources) and for the risk category of 'other vehicle-generated impacts'.

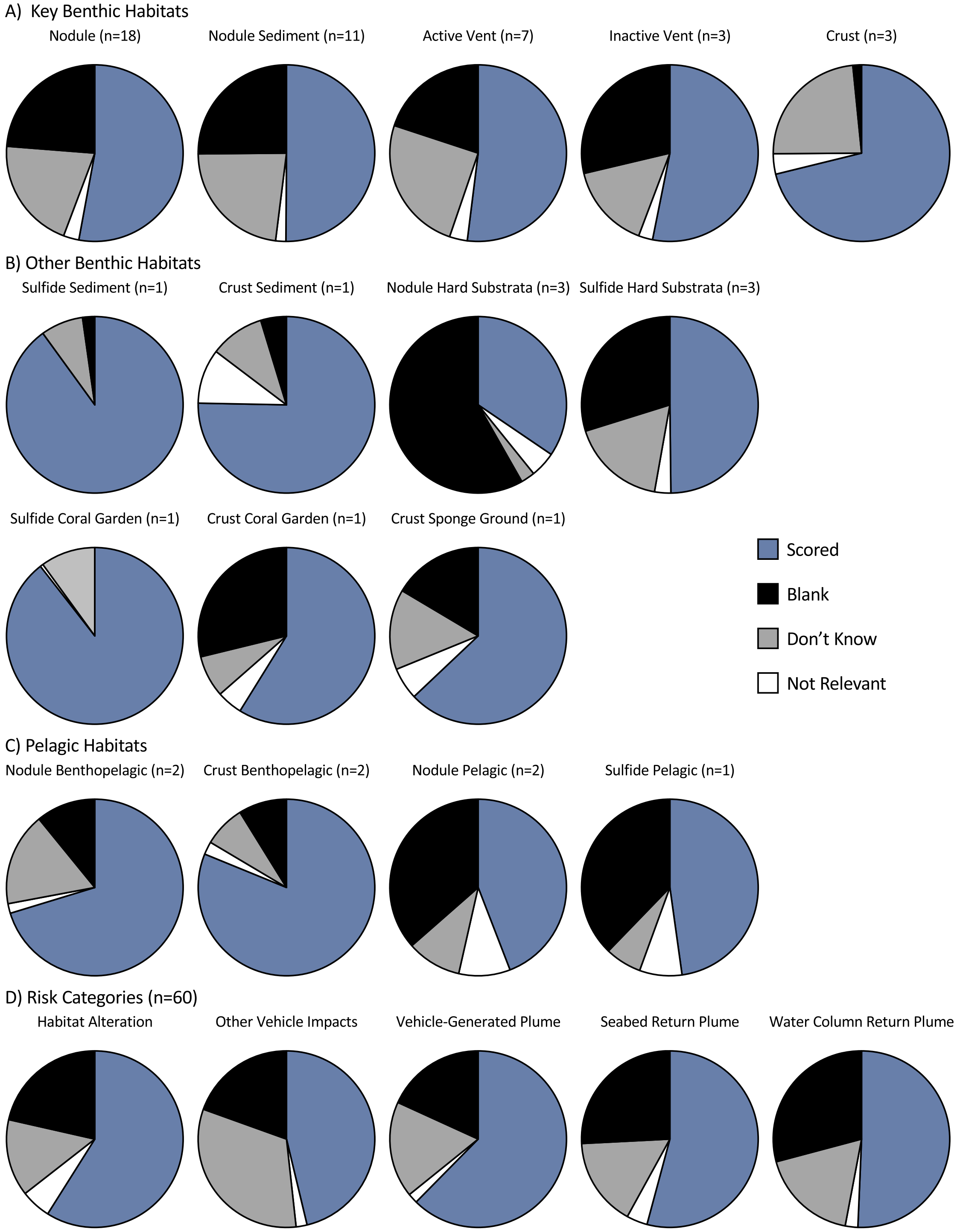

Fig. 2. Uncertainties and knowledge gaps. The percentage of habitat vulnerability measures for each habitat (A–C) and for each risk category (D) that were i) Scored, i.e., assigned vulnerability scores, ii) Blank, iii) Don't Know, or iv) Not Relevant, i.e., not relevant to the mining scenario. A–C: n is the number of respondents; D: n is the number of responses.

3.4.2. Habitat vulnerabilities by risk source for all habitats

3.4.2.1. Key benthic habitats. The five risk sources of greatest concern based on their ranked overall habitat vulnerability scores (Supplementary File 3: Table S3) differed among the key benthic habitats: The nodule habitat was perceived to be most vulnerable to risk sources associated with habitat alteration, including habitat removal and changes to the nodule surface that might affect recruitment, while nodule sediments were considered to be most vulnerable to plume effects, including changes in seawater chemistry, toxicity, and burial. Active and inactive vent habitats were perceived to be most vulnerable to risks associated with habitat alteration, including physico-chemical changes in fluid composition, fluid flux, and hydrography owing to vehicle activities as well as to changes in POC flux by a return plume at the seabed. Crusts were perceived to be vulnerable to habitat alteration (habitat removal and changes in hydrography), as well as plume effects (toxicity, turbidity).

The five risk sources of least concern also differed among the key benthic habitats (Supplementary File 3: Table S4). Overall, several risk sources associated with water column return plumes (light attenuation, masking of bioluminescence, light pollution, and release of CO_2 into the upper water column) were generally not of concern. Species introductions and electromagnetic radiation as ‘other vehicle impacts’ were also among risk sources of low concern.

3.4.2.2. Other sediment and hard substrata habitats. Few experts scored vulnerability measures for sediment associated with sulfide and crust resources or for other hard substrata associated with nodule (e.g., seamount basalt) or sulfide resources (e.g., ridge basalt). Risk sources of greatest concern for these other benthic habitats were mostly those associated with seabed return plumes, but the specific risk sources of greatest concern were diverse (Supplementary File 3: Table S5). There were a number of risk sources associated with water-column return plumes that were considered to be of no concern for some of these other habitats (Supplementary File 3: Table S6), including, for example, light attenuation, masking of bioluminescence, and release of CO_2 into the upper water column for sediment associated with sulfide resources.

3.4.2.3. Coral gardens and sponge grounds. Each vulnerability measure for these habitats was scored by only a single expert (Supplementary File 3: Tables S7, S8). The top perceived risk sources for coral gardens and sponge grounds included those associated with ‘other’ vehicle impacts (introduced species, noise) and with habitat alteration (habitat removal). Seabed return plumes and vehicle generated plumes were also among the top risk categories, with clogging of filter-feeding

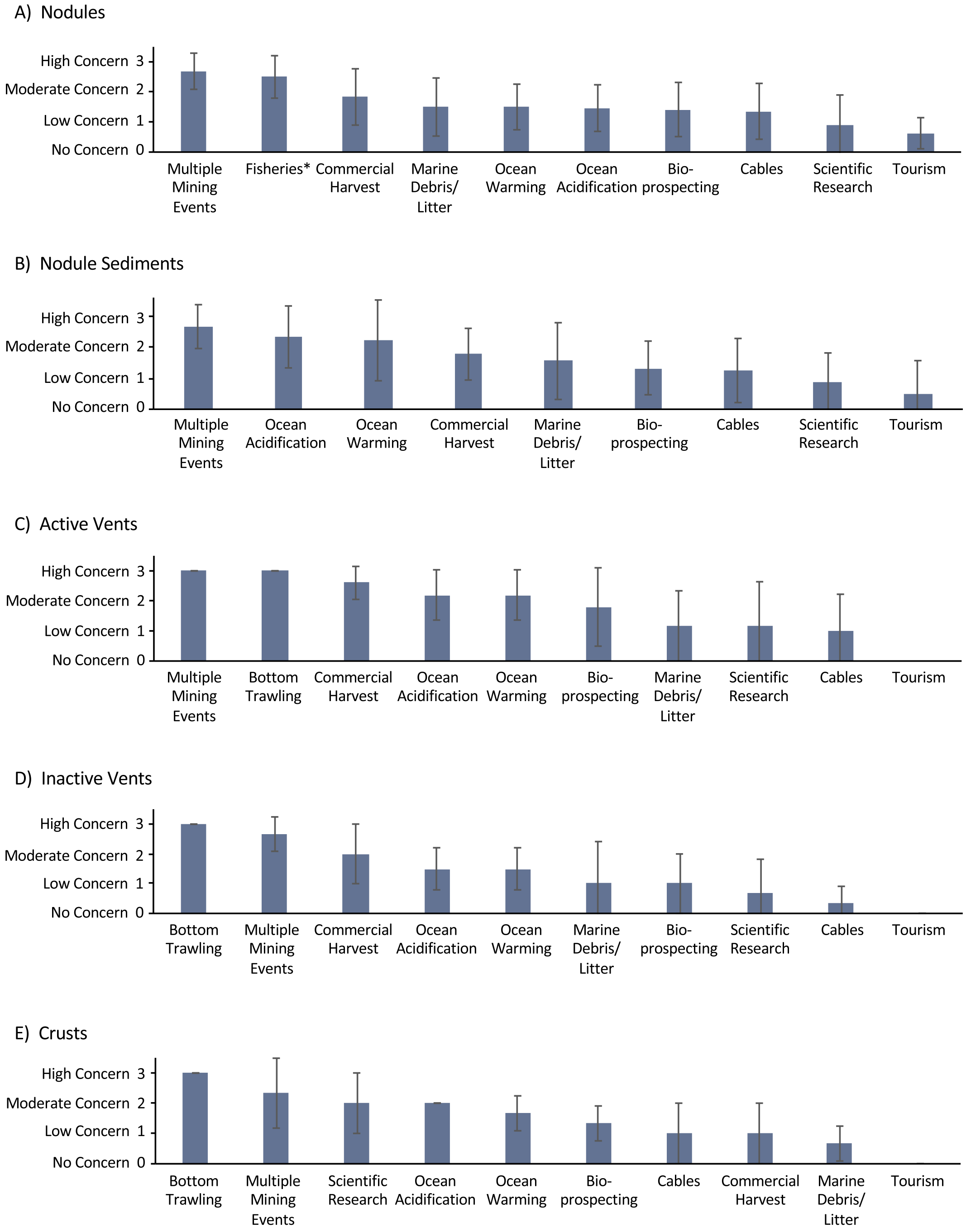

Fig. 3. Expert opinion regarding concern about different types of cumulative impacts (mean score ± S.D.). *Fisheries was identified as an additional impact by two respondents in nodule habitats.

structures and toxicity the top risk sources. Nineteen risk sources were of no concern whatsoever according to the expert response for some coral and sponge habitats, including sunlight attenuation, masking of bioluminescence, light pollution, and electromagnetic radiation.

3.4.2.4. Benthopelagic and pelagic habitats. Again, few experts scored vulnerability measures for benthopelagic and pelagic habitats (Supplementary File 3: Tables S9, S10). For benthopelagic habitats associated with nodule resources, respondents focused on risk sources associated with the benthic component, including smoothing, burial, and changes in porewater chemistry. For the benthopelagic habitat associated with crusts, the top risk sources were all associated with plumes, including toxicity, nutrient enrichment, and altered water chemistry. For pelagic environments associated with nodules, CO_2 transfer from deep to shallow water was perceived to be a top risk, along with effects of increased turbidity from a water-column return plume (masking of bioluminescence, clogging of filter-feeding structures), toxicity, and altered water chemistry. For the pelagic habitat associated with sulfide resources, introduced species, toxicity, and turbidity effects were perceived to be top risks. Five risk sources associated with water-column return plumes were ranked lowest for benthopelagic habitats associated with nodule resources and included release of CO_2 into the water column and light attenuation. For the benthopelagic habitat associated with crust resources, light attenuation caused by the vehicle-generated plume and increased habitat heterogeneity were lowest ranked risk sources. Experts were least concerned about nutrient enrichment and increased POC deposition for pelagic environments associated with nodule resources and about altered hydrography and light pollution for pelagic environments associated with sulfide resources.

3.4.3. *Cumulative impacts*

Experts expressed greatest concern about the vulnerability of habitats to cumulative impacts resulting from multiple mining events and fishing activities (Fig. 3), and there was moderate to high concern about commercial harvests for the biotechnology industry associated with nodule and vent habitats. Ocean acidification and ocean warming tended to be of moderate concern for all habitats. There was low concern regarding cumulative impacts of scientific research, marine debris, cables, bioprospecting, but variances were large. Cumulative impacts of tourism were of no or low concern.

4. Discussion

Striking outcomes of the survey include i) the relative paucity of experts willing and able in 2016 to offer an opinion about vulnerability of mineral-associated habitats to a variety of risk sources, ii) the low response rate for all habitats associated with cobalt crusts, as well as for benthopelagic, pelagic, coral, and sponge habitats associated with mineral resource environments, iii) the relative lack of consensus regarding the most likely biological consequences of impacts from top-ranked risk sources except for the expected low likelihood of regional/global extinctions resulting from mining, iv) the high perceived vulnerability of deep-sea habitats to habitat destruction, plume burial and plume toxicity, as well as cumulative impacts from multiple mining events and fishing pressure, v) the relative lack of concern for ‘other’ vehicle impacts, and vi) the overriding uncertainty among respondents about vulnerabilities of these habitats to any risk category, apart from habitat alteration. Even for habitat alteration, there was never ‘very high certainty’ regarding habitat vulnerability scores. These outcomes underscore and help to quantify the paucity of knowledge and expertise regarding deep-sea ecosystems and processes, as already argued by (Boetius and Haeckel, 2018; ECORYS, 2014; Jones et al., 2018; Le et al., 2017; Lodge and Verlaan, 2018; Miller et al., 2018; Ramirez-Llodra et al., 2015), among many others.

The literature on risk assessment and environmental impacts of deep-sea mining is replete with potential risk sources (Table 2), but they have not been prioritized. A key need for effective environmental management is guidance on where and what kind of baseline assessments, monitoring, and mitigation efforts should be undertaken in response to a prioritized list of risk sources.

This study assessed habitat vulnerability to specific risk sources and broader risk categories, but has a number of limitations, including the unwieldy scope of the survey, which may have been onerous for respondents and could have resulted in entry errors and incomplete surveys; ambiguities arising from varying interpretations of survey questions; and no means of calibrating scores for the habitats considered, given that most individuals only scored vulnerability measures for a single habitat. Further, the potential for biased responses (Martin et al., 2012; Tversky and Kahneman, 1974) was not explicitly managed. In hindsight, some of the SICA vulnerability measures might be better assessed using different metrics. For example, the percentage of habitat impacted may be a better metric than the spatial scale of the impact of mining, given differences in the style of mining: for active and inactive vents, while the spatial scale may be limited, a very high percentage of the habitat would be removed during mining (Weaver et al., 2018). Further, in the two years since the survey was deployed, there has been some increase in knowledge of and global engagement in deep-sea environmental management, which will have resulted in evolving expert perceptions. Nevertheless, the survey outcomes offer a preliminary ranking of the perceived vulnerability of different deep-sea habitats to potential risk sources and highlights the fact that all risk sources are not perceived as equal. Polling outcomes also demonstrate that the most likely biological consequences differ among habitats for a given top-ranked risk source and that there is not always consensus among experts regarding what the most likely biological consequences of a top-ranked risk source might be. Regional and global extinctions were among the biological consequences that were often considered least likely for the key benthic habitats, but the level of certainty for these responses was not assessed. Cumulative impacts are a general concern (Gollner et al., 2017; MIDAS, 2016a,b; Ramirez-Llodra et al., 2011), and of the many possible options, experts perceived multiple mining events, fisheries activities, and climate change to be among the highest concerns and thus important to understand.

Deep-sea habitats associated with mineral resources were considered by experts to be most vulnerable to risks associated with habitat removal and with sediment plume effects, including metal toxicity and burial. These finding hold for both the polling and SICA approaches used here. Mitigation addressing impacts of these risk sources is already in development; the relevance and importance of such investments is underscored by this expert opinion. Protection of up to 50% of representative seabed habitats from mining activities is recognized as a critical and precautionary mitigation effort at the regional scale for the impacts of habitat removal and alteration (Lodge et al., 2014), but these networks of protected-areas need to be designed in a manner that achieves environmental management objectives (Dunn et al., 2018). Modeling efforts related to reducing the ecological impacts of vehicle-generated plumes point to mitigation approaches that confine sediment deposition to a small area by, for example, reducing height of plume and increasing the settling velocity by increasing particle aggregation (Peukert et al., 2018). These management strategies could potentially limit the areal extent of smothering and fouling of benthic organisms and minimize the footprint of toxic metals in the environment. Still other mitigation efforts begin with recommendations on how to quantify potential risks, such as the “Weight of Evidence” (WOE) approach advocated by Hauton et al. (2017) to identify high-risk mineral resources or high-risk communities relative to metal toxicity. In such a WOE approach, once high-risk sources are identified, targeted mitigation measures can be put in place, including actions such as modifications to operating procedures, mining tool design, and extraction from lower-risk areas. A key step in the WOE approach is the use of multiple lines of evidence obtained through research on environmental toxicity, including, for example, characterization of toxic element leachability (Fuchida et al., 2017), ecotoxicological experiments (Santos et al., 2018), and particle dispersion and deposition models (Lopes et al., 2019). Experiments and observations related to ecological consequences of burial of organisms and smothering and clogging of filter-feeding structures and respiratory organs by particulates (e.g., Bell et al., 2015; Hendrick et al., 2016) or of metal-enriched sediment deposition on hard-substratum habitats (e.g., Lawes et al., 2017) can be readily found in the shallow-water literature, but are rare in the deep sea.

'Other' vehicle and installation impacts—light, electromagnetic radiation, noise, introduced species—were among the lowest ranking risk sources in terms of habitat vulnerability scores across habitats, but there was a high degree of uncertainty associated with these scores. Light has been implicated in the degradation of the photoreceptors of shrimp at hydrothermal vents on the Mid-Atlantic Ridge following brief exposures to submersible lights during scientific collections (Herring et al., 1999), but there is no evidence that shrimp populations have declined in response (Copley et al., 2007). It is challenging to point to substantive research on vulnerability of deep-sea benthic ecosystems to low-ranking risk sources at spatial and temporal scales, intensities, and frequencies relevant to mining activities. Shallow-water studies, however, alert us to sensitivities of marine vertebrates and invertebrates to marine soundscapes and noise pollution (Williams et al., 2015), including the role of sound in larval recruitment and settlement processes (Lillis et al., 2013), and to behavioral responses to electromagnetic fields by elasmobranch fish and marine mammals (Gill, 2005). Research suggesting the presence and even active use of the seabed by marine mammals is increasing in areas associated with deep-sea mining (Marsh et al., 2018). Risk sources that might affect organisms in the water column are readily identified (Table 2), but the potential to cause serious harm to water column ecosystems is not understood (Hauton et al., 2017; Levin et al., 2016). Experts provided limited insight into perceived vulnerabilities of benthopelagic and pelagic habitats to risk sources associated with mining activities.

5. Conclusions

Key benthic habitats associated with deep-sea mining are perceived to be vulnerable to risks associated with habitat alteration with a high degree of certainty. For other risk sources, vulnerabilities are poorly constrained. Given the paucity of deep-sea experts and the substantial uncertainties of expert opinions elicited here, there remains a critical and urgent need for resource and site-specific modeled and measured baselines and monitoring methods. There is also a strong need for determination of acceptable thresholds for all potential risk sources and biological consequences, even for lower ranked risk sources and habitats perceived to be less vulnerable. Scientific data will be important for informed guidance and decision-making as the ISA fulfills its obligations to protect and preserve the marine environment (Jaeckel, 2016; Lodge and Verlaan, 2018), and for effective responses to indications of impending serious environmental harm.

Risk assessment must progress from expert opinion with low certainty to data-rich and ecosystem-appropriate assessments using methods that improve the accuracy and information content, manage biases, and capture uncertainty of judgement with better metrics (Martin et al., 2012; Morgan, 2014). As ecological risk assessments mature, they can inform effective precautionary and mitigation efforts designed and deployed in advance of commercial exploitation. Such efforts will need to include procedures for adaptive management as new information arises. Test mining with robust environmental impact assessments are acknowledged as key steps toward delivering quantitative measures of risks and biological consequences (Lodge and Verlaan, 2018). Decision makers must remain cognizant of the immense knowledge gaps that persist in understanding environmental consequences of deep-sea mining activities and the slow pace at which this knowledge can be acquired, disseminated, and vetted by the expert community.

Data availability

Survey data from which all tables and figures were developed are archived in a Mendeley Data Repository.

Declarations of interest

None.

Acknowledgements

We thank Jeff Ardron, Maria Baker, David Billett, Rachel Boschen-Rose, Malcolm Clark, Andy Gooday, Lenaick Menot, Gordon Paterson, Hans Torre Rapp, and Les Watling for their advice throughout the design of the risk assessment survey. Austin Smith (Duke University) assisted as an intern in the early development of this project. We are especially grateful to the 33 individuals who participated in the survey. This manuscript benefitted from thoughtful comments from the editor and reviewers. Funding: This project was supported by the Global Ocean Biodiversity Initiative through the International Climate Initiative (IKI; grant number 16_IV_049_Global_A_Global Ocean Biodiversity Initiative GOBI). The Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety (BMU) supports IKI on the basis of a decision adopted by the German Bundestag. This work also represents a contribution to the MIDAS Project, which received funding from the European Union's Seventh Programme for research, technological development and demonstration under Grant Agreement No. 603418. The funding sources had no involvement in this research effort.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2019.04.014.

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