DEEP-OCEAN STEWARDSHIP INITIATIVE

DOSI

INFORMATION SHEET

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Ecotoxicological risks of deep-sea mining: Scientific context and evidence

Key messages

- This Information Sheet summarises the current state of knowledge on the ecotoxicity risks of deep-sea mining for policymakers and stakeholders.
- For policy relevance and recommendations, see the related Policy Brief – DOSI (2026) Towards an ecologically meaningful toxicity assessment of deep-sea mining

Why ecotoxicology matters for deep-sea mining governance

Ecotoxicology is the study of how chemical contaminants affect living organisms and the ecosystems they belong to. It links molecular and cellular responses to population- and ecosystem-level outcomes, and provides the scientific basis for environmental thresholds and the concentrations or conditions at which exposure is likely to cause harm. Chemical contamination is among the least-characterised environmental risks of deep-sea mining (DSM). Mining operations are likely to disturb, resuspend and redistribute metals and persistent organic pollutants (POPs) that have accumulated in abyssal sediments, increasing their availability to deep-sea organisms, both on the seafloor via collector plumes and in the water column via discharge plumes. Understanding ecotoxicological risk is directly relevant to the **International Seabed Authority (ISA)** guidelines, where the concept of **"serious harm" requires evidence of biological effect, not simply the presence of a chemical**. Without validated effects-based indicators, it is not possible to distinguish natural background variation from mining-driven change, or to demonstrate that a threshold has or has not been crossed. Establishing this evidence base is therefore not only a scientific priority but a regulatory one also.

Contamination pathways and exposure risk

Deep-sea sediments act as long-term sinks for contaminants delivered from surface waters, including metals and POPs[1,2]. **DSM is expected to disturb these sediments, releasing and redistributing accumulated contaminants, and increasing their bioavailability to exposed mid-water and deep-sea organisms**[3]. Metals have been the primary contaminant of concern in DSM because of their known prevalence and potential to accumulate in sediments rich with polymetallic nodules. Once taken up by deep-sea organisms, metals can interfere with biological processes, potentially disrupting physiology, growth, reproduction, behaviour, and survival, even at low bioavailable environmental concentrations[4] (**Table 1**).

Table 1: Key pathways, routes of exposure, and risks associated with deep-sea mining.

Pathway	Route of exposure	Risk
Direct water column exposure	Dissolved metals and suspended particles released during plume dispersion come into contact with organisms across a wide area.	Even short-term exposure at low concentrations can disrupt enzyme function, impair respiration, and trigger cellular stress responses.
Sediment ingestion	Deposit feeders ingest contaminated particles directly; filter feeders passively accumulate suspended particles from the water column. Fine-grained particles are particularly efficient at binding and transporting metals and POPs.	Filter feeders lack the gut adaptations that allow some deposit feeders to reduce metal uptake during digestion. Neither group is protected against POPs, which accumulate in fatty tissues regardless of gut chemistry. Chronic ingestion leads to tissue accumulation and progressive physiological harm.
Trophic transfer	Contaminants bioaccumulate in prey organisms and biomagnify through food webs, increasing concentrations at higher trophic levels.	Predators may carry the greatest contaminant burden. When they die, their carcasses deliver concentrated contaminants to scavenging and seafloor communities.
Far-field transport	Mobile species range widely across and beyond DSM contract areas.	Ecological risk extends into areas not subject to direct mining impacts, including Areas of Particular Environmental Interest (APEIs) and potentially across jurisdictional boundaries relevant under the Biodiversity Beyond National Jurisdiction (BBNJ) Agreement.

As the time and intensity of exposure increase, impacts intensify. At sublethal levels, organisms may exhibit impaired feeding, behaviour, or reproduction. At higher exposures, mortality can occur, directly altering community structure. When combined with stressors already characteristic of deep-sea environments, particularly limited food supply, even low-level contaminant exposure could ultimately prove fatal. Mining-related exposures are likely to be chronic and continuous, sustained over the full timescale of operations, and across a spatial scale that, as the industry expands, may leave little opportunity for organisms to escape exposure entirely. **These individual-level effects scale up over time, altering ecosystem structure and function, yet the detectability of effects using currently available tools remains low throughout**[3,4] (**Figure 1**).

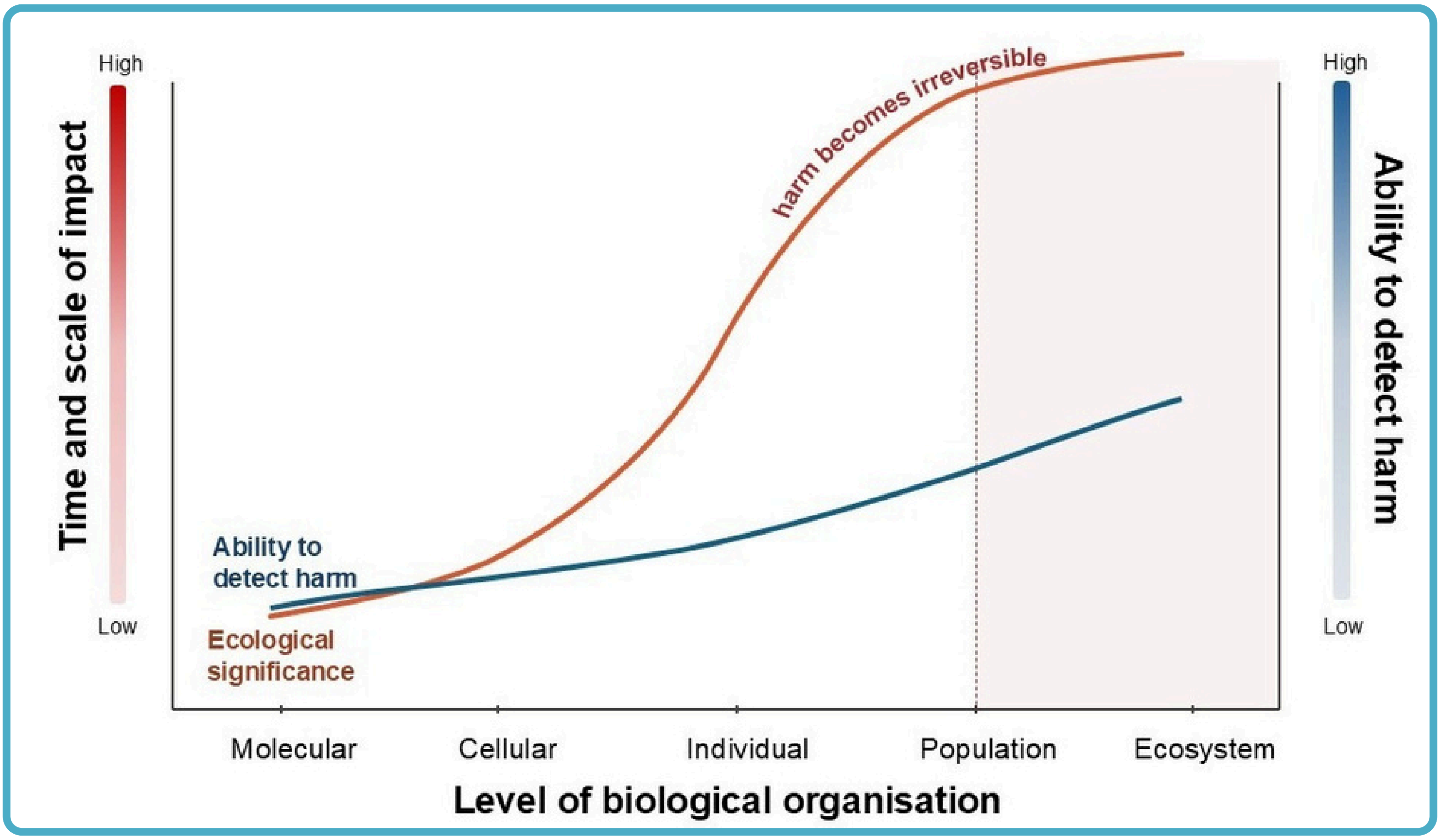

Figure 1: *Relationship between ecological significance and detectability of contaminant effects across levels of biological organisation. Ecological significance (orange) increases from the molecular to the ecosystem level, while detectability with current tools (blue) remains low throughout. The shaded area represents the range across which effects become irreversible.*

Contaminant effects cascade through multiple levels of biological organisation, from cellular disruption to ecosystem-level change (**Figure 2**). **Early detection depends on identifying signals at the lowest levels, before harm becomes irreversible.**

- **Molecular and cellular effects:**
  Metal exposure can disrupt enzymatic processes, generate oxidative stress, damage DNA, and impair immune function. These cellular responses are the earliest detectable signals of contaminant harm, and form the basis of biomarker-based assessment. Validated biomarkers allow regulators to detect harm earlier, and at lower concentrations, than by waiting for population-level outcomes. However, biomarkers developed in shallow-water species may not translate to deep-sea organisms, whose biochemical adaptations to high pressure, low temperature, and food limitation may alter the baselines, sensitivity to contaminants and the expression of standard stress responses[5].

- **Sublethal effects on individuals:**
  Cellular stress results in sublethal effects on individuals – impaired foraging, reduced growth, and reproductive failure. In the food-limited deep sea, where energy budgets are extremely tight, the metabolic cost of responding to contaminant exposure can have greater consequences than in shallow-water species. Studies using shallow-water proxies suggest that metal exposure can disrupt these functions at low concentrations[6], but whether this holds for deep-sea organisms, which have evolved under very different conditions, remains unknown.

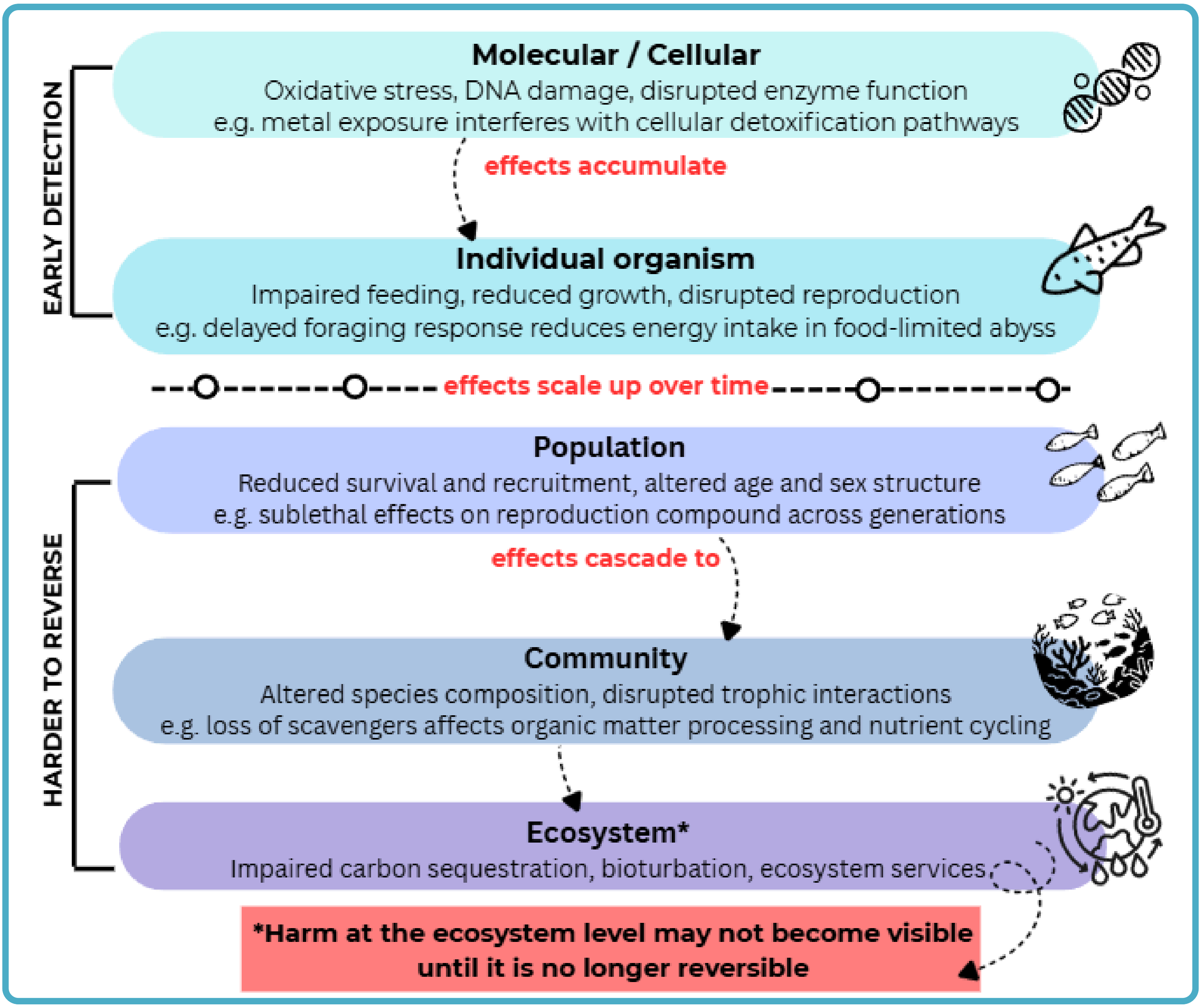

Figure 2: *How contaminant effects scale from the cellular level to ecosystem-level consequences and how the most serious harm may go undetected until it is irreversible.*

- **Population and ecosystem consequences:**
  Individual-level effects scale up to reduced reproductive rates, altered community composition, and disrupted ecosystem functions; outcomes directly relevant to "serious harm" under ISA guidance. Recovery timescales in abyssal systems may span decades to centuries, and interactions between chemical contamination and co-occurring stressors, including sediment disturbance, warming, and acidification, are poorly understood. The ecosystem-level consequences of DSM therefore carry substantial uncertainty.

Current state of knowledge

Despite the clear regulatory need, the evidence base for deep-sea ecotoxicology remains critically limited. Key gaps include:

- **Validated biomarkers:** Commonly used indicators of toxicity have not been validated for abyssal species. Benchmark values from coastal organisms cannot be applied directly, and in some cases may mislead, as high pressure can suppress rather than activate standard stress responses in deep-sea species.
- **Chronic toxicity thresholds:** Acute lethal concentrations exist for a small number of deep-sea species. However, chronic effect concentrations, most relevant to long-term DSM exposures, are absent.
- **Baseline contaminant data:** Tissue concentration data are spatially sparse, taxonomically narrow, and temporally short, making it difficult to characterise natural variability or changes driven by DSM activities.
- **Multiple stressor effects:** Organisms are never exposed to contaminants in isolation. DSM introduces chemical stressors alongside physical disturbance, while climate change is simultaneously altering currents, food availability, temperature, oxygen, and pH. Few studies have examined these interactions, and effects produced by multiple stressors in combination are not predictable from single-stressor studies.

Practical constraints compound these gaps. Organisms experience decompression stress during collection, which can alter biomarker responses and tissue chemistry. Logistical costs restrict spatial and temporal replication. Without a coordinated strategy to address these challenges, ecotoxicological harm from DSM risks continues to be undetected.

What current evidence tells us

Field data from the Clarion-Clipperton Zone (CCZ) and experimental studies using mining-relevant materials together provide an emerging picture of ecotoxicological risk. Contaminant concentrations in deep-sea sediments and biota from mining target areas in some cases exceed those recorded in coastal environments affected by anthropogenic pollution. **Experimental evidence consistently shows that exposure to mining-relevant materials causes biological harm at realistic concentrations**. The studies are few, and none fully replicate deep-sea or open-ocean conditions; however, across different organisms, contaminant types, and experimental approaches, current evidence concludes that existing risk frameworks are not equipped to detect or quantify harm under true environmental conditions.

Contaminant baselines from the CCZ

Detecting the ecotoxicological effects of DSM requires robust baseline data. At present, baseline information on contaminant concentrations in tissues of deep-sea species remains limited across most regions targeted for mining[2,7]. **Data are spatially, taxonomically and temporally restricted, making it difficult to define natural variability and establish reliable reference ranges, or derive defensible environmental thresholds**. Recent syntheses emphasise that threshold values developed for shallow-water systems may provide useful starting points but cannot be directly related to deep-sea environments without validation under abyssal conditions[4].

Field evidence from the eastern CCZ indicates that **deep-sea grenadiers** (**Figure 3**) **accumulate contaminants at concentrations that would be of ecotoxicological concern in other marine environments**[2,7]. The deep-sea grenadiers have high concentrations of metals in their tissues, including mercury (Hg) and cadmium (Cd), consistent with dietary exposure and bioaccumulation in deep-sea food webs[7]. Many individuals exceed the 0.2 mg/kg Hg accumulation threshold considered protective for fish health[8]. Observed cadmium concentrations also exceed known thresholds for sublethal effects associated with reduced growth and reproductive impairment in other fish species[9].

Figure 3: *Deep-sea grenadier from the CCZ (Image provided by M M Cecchetto).*

Similarly, POPs, including polychlorinated biphenyls (PCBs) and per- and polyfluoroalkyl substances (PFAS), have been detected in abyssal sediments and biota, demonstrating that persistent anthropogenic contaminants can reach abyssal sediments and biomagnify in deep-sea ecosystems[2]. **The observed levels in fish tissues were comparable, and in some cases, even exceeded tissue concentrations in freshwater and coastal systems**. Sediment concentrations of different POPs (i.e., PCBs, PFAS, Polybrominated diphenyl ethers (PBDEs)) varied considerably across the region, reflecting different transport pathways to the seafloor. PCBs were relatively uniformly distributed, consistent with steady sinking of contaminated particles, while PFAS and PBDEs showed much higher spatial variability, likely driven by episodic events such as carrion-fall and vertically migrating organisms. Consequently, more data are needed to understand and map where high sediment POP concentrations exist, as sediments with high POP concentrations may be unknowingly resuspended in deep- and mid-water ecosystems where they could enter food webs through routes that are currently uncharacterised.

Together, these findings indicate that demersal fishes in the CCZ already carry substantial burdens of non-essential metals and POPs. Mining is therefore unlikely to initiate contamination but may disturb and redistribute existing contaminant pools across wider spatial scales. However, **baseline data remain spatially sparse and temporally unresolved, limiting our ability to characterise natural variability, long-term trends, and cumulative exposure**. Although elevated tissue concentrations do not necessarily equate to ecological harm, and deep-sea species may possess physiological adaptations to naturally metal-rich environments, their tolerance thresholds and capacity to cope with additional anthropogenic inputs remain largely unknown. Monitoring based solely on tissue concentrations risks overlooking ecological consequences; robust assessment requires biologically meaningful, effects-based indicators, validated biomarkers, and food-web-scale evaluation of exposure and risk.

The challenges of establishing effects-based baselines for deep-sea species are illustrated by a recent study to measure DNA damage in deep-sea grenadiers collected from the CCZ at depths greater than 4,000 m. Despite novel methodological approaches to process samples at sea, interpreting the results is fundamentally complicated by the absence of a true control. All fish collected experienced decompression during retrieval, which may itself cause DNA damage. This makes it difficult to determine whether measured levels reflect natural background or collection stress[10]. By extension, **the effects of sampling complicate our ability to detect any additional effect attributable to mining-related contamination**. This illustrates a broader limitation to establishing meaningful ecotoxicological baselines for deep-sea species.

Evidence for the toxicological potential of deep-sea mining

Though limited, **available evidence shows that sediments and minerals from areas targeted for DSM cause measurable harm to marine life** (**Figure 4**). Existing studies vary in how closely they reflect real deep-sea conditions. Few have tested deep-sea species under the conditions of their natural habitat, and this gradient reflects the genuine difficulty of deep-sea ecotoxicology. **In laboratory experiments, toxic effects at realistic exposure levels have been observed across a number of organisms** under a range of temperatures and pressures. This consistency across such different approaches lends weight to the underlying concern. However, what remains unknown is how severe that harm is for deep-sea organisms living under true deep-sea conditions.

A study using a deep-sea pelagic jellyfish, *Periphylla periphylla*, exposed to abyssal sediment under shipboard conditions provides clear evidence of multi-stressor interactions[11]. Sediment plume exposure alone provoked an acute and energetically costly response, triggering excess mucus production and upregulating genes associated with aerobic respiration and wound repair. **When combined with a modest temperature increase, the effects of sediment exposure are compounded**. These findings highlight the risks to organisms in the water column, not just the seafloor.

A study testing metals released from disturbed CCZ sediments found that metals cause measurable toxicity individually, but that interactions between multiple metals alter toxicity in complex and unpredictable ways. Manganese, for example, which has the potential to be released at high concentrations during sediment disturbance, enhances the toxicity of copper and chromium by up to 230%[12]. Meanwhile, copper and chromium were more toxic at low temperatures experienced in the deep sea (4°C) compared to higher temperatures (20°C), while cadmium showed the opposite pattern. **Single-metal risk frameworks derived from ambient-temperature laboratory conditions may therefore underestimate the toxicity of real DSM discharges**, which involve complex metal mixtures released into cold water.

Experiments exposing a deep-water habitat-forming cold-water coral to polymetallic sulphide particles at realistic plume concentrations resulted in 100% mortality within 27 days of exposure[13]. Death resulted from the combined mechanical and chemical effects of the particles (e.g. physical clogging prevented feeding), while copper accumulated in tissues at concentrations far exceeding known toxicity thresholds. Notably, standard cellular stress biomarkers were suppressed rather than activated in dying organisms, illustrating how **conventional monitoring tools may fail to detect harm** before it becomes irreversible.

Another study evaluated the environmental risks associated with deep-sea mining by examining how sediments from polymetallic nodule fields affect a shallow-water marine mussel, *Mytilus galloprovincialis*[6]. Mussels were exposed to realistic concentrations of deep-sea sediments collected from the CCZ. The results show that these **sediments release bioavailable metals and rare earth elements into seawater, which can then be taken up by marine organisms**, raising concerns about the broader impacts of sediment plumes generated during mining operations.

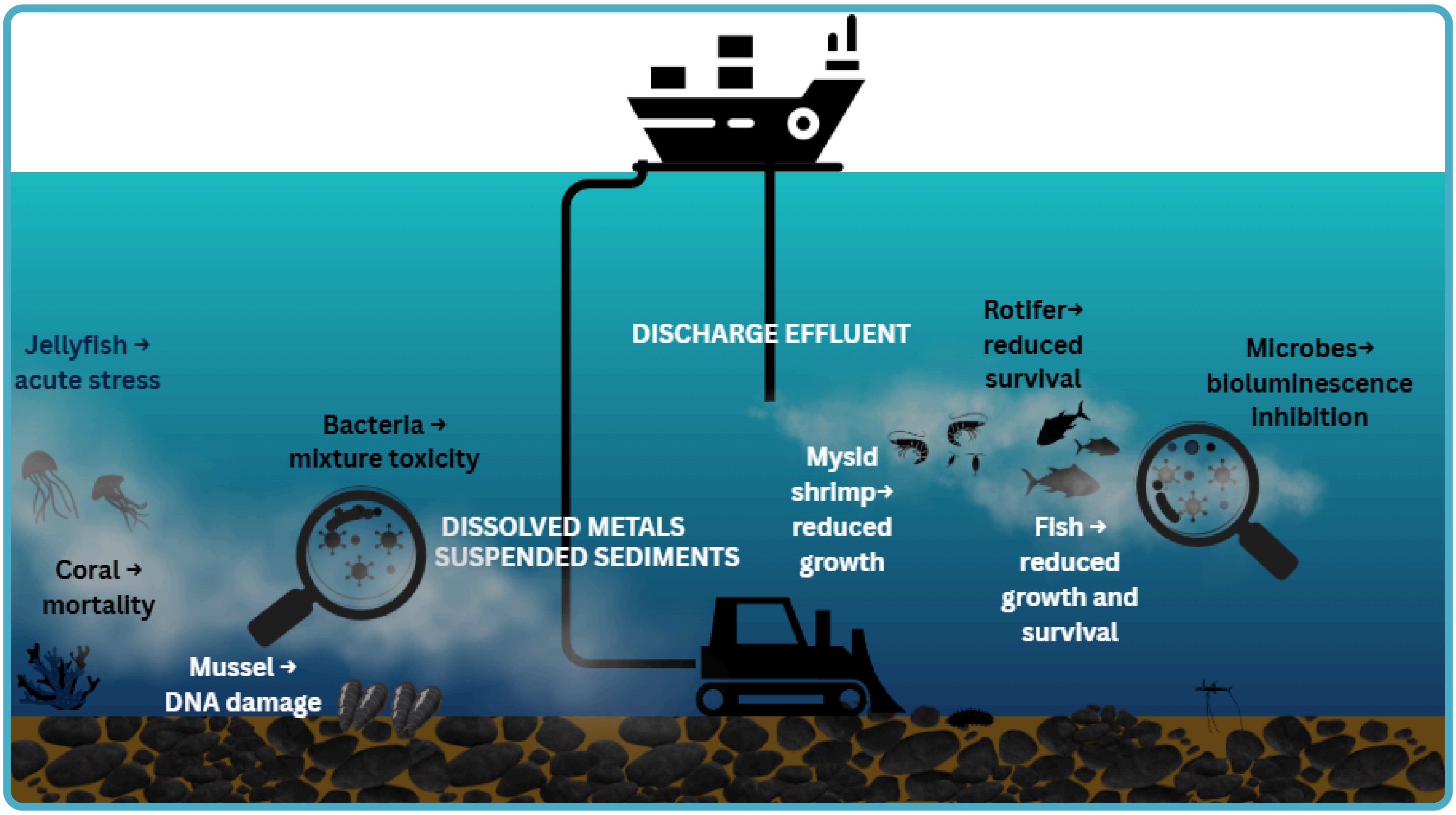

Figure 4: Experimental evidence of ecotoxicological harm from deep-sea mining-relevant exposures.

The study further found that short-term exposure (14 days) to relatively low sediment concentrations led to measurable biological effects. Mussels accumulated metals, particularly manganese, and exhibited signs of physiological stress, including disruption of detoxification and antioxidant systems. Importantly, exposure caused inhibition of key neurological functions and significant DNA damage, indicating both neurotoxic and genotoxic effects. These findings demonstrate that **disturbance of deep-sea sediments can affect organism health at cellular and molecular levels, even at distance from the mining site**.

Most recently, a study examined the toxicity of only the aqueous portion of mining effluent (particulates in effluent were removed, including identified microplastics) collected just prior to discharge to the mid-water ecosystem[14]. In this study, model marine microbial, invertebrate, and fish laboratory species were exposed to the dissolved constituents in the discharge DSM effluent, and only apical endpoints (lethality, reduced growth) following short-term exposures (maximum of 2–7 days) were recorded. **Short-term exposure to DSM effluent resulted in significant toxicity across all tested species**. Additionally, the variability in toxicity-test results, along with order-of-magnitude ranges in measured contaminants, reinforces the need for further study of DSM effluent to effectively evaluate potential ecotoxicological effects to mid-water and abyssal ecosystems and the consequences of longer-term exposure to DSM effluents (including both dissolved and particulate fractions).

While these studies are best understood as indicative of toxicological potential rather than direct predictions of risk in the natural environment, they present a **strong argument for investment in deep-sea validated approaches**. Overall, the research highlights that sediment plumes from deep-sea mining could pose substantial ecological risks, with potential consequences for biodiversity, food webs, and ecosystem functioning. The observed effects at low exposure levels suggest that impacts may be amplified under full-scale industrial mining. These studies therefore **underscore the need for precautionary regulation, improved environmental monitoring, and further research to define safe operational thresholds** before large-scale deep-sea mining is undertaken.

Summary

Deep-sea sediments already carry significant concentrations of metals and persistent pollutants, the legacy of decades of atmospheric and oceanic transport into one of the least-disturbed environments on Earth. DSM is expected to resuspend these sediments and contaminants in both the deep sea and in mid-water ecosystems, increasing the bioavailability of the metals and pollutants already locked within them, and will spread that exposure beyond contract boundaries through plume dispersal and mobile fauna, adding to baseline contamination whose biological significance is not yet understood.

The biological consequences of contaminant exposure cascade from molecular disruption to ecosystem-level change, with the most serious harm often the hardest to detect until it is no longer reversible. Despite this, the tools needed to monitor and assess that harm, including validated biomarkers, defined toxicity thresholds, and an understanding of how multiple stressors interact, remain largely absent for deep-sea species. Without these early-warning indicators, current efforts to manage and avoid biodiversity loss from deep-sea mining lack the evidence base they need, focusing on what can be observed rather than what would actually signal harm in time to act. Existing evidence, though limited and drawn from organisms and conditions of varying environmental realism, consistently concludes that DSM causes measurable harm. Closing this evidence gap is essential to ensuring that DSM governance is objectively effects-based.

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About DOSI

The Deep-Ocean Stewardship Initiative is a global network of experts that integrates science, technology, policy, law and economics to advise on ecosystem-based management of resource use in the deep ocean and strategies to maintain the integrity of deep-ocean ecosystems within and beyond national jurisdiction.

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