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Environmental impacts of deep sea mining: a comprehensive review of regulatory frameworks and ecological risks

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Abstract

Deep sea mining (DSM) is an emerging frontier in global resource development, driven by demand for critical minerals needed for the energy transition. The International Seabed Authority (ISA) has issued 31 exploration contracts covering more than 1.3 million km² of sea floor; however, exploitation regulations remain unresolved and the governance capacity of contracted states is a growing concern. This rapid review evaluates key environmental impact pathways, including habitat destruction, biodiversity loss, sediment plume generation, disruption of oceanic carbon sequestration, impacts on pelagic ecosystems and fisheries-dependent communities and long-term ecosystem alteration. Evidence synthesised indicates DSM poses substantial and potentially irreversible risks to marine ecosystems, with recovery timescales potentially extending from centuries to millennia. Restoration is scientifically unproven and economically prohibitive, with the only peer-reviewed deep sea restoration cost estimate reaching up to USD75 million per hectare. Post-impact restoration cannot be treated as a credible mitigation or offset mechanism. Many states holding exploration contracts exhibit limited regulatory capacity, weak treaty compliance and elevated institutional risk. The findings underscore the urgent need for precautionary governance frameworks, strengthened environmental baseline monitoring and enhanced international oversight before commercial-scale DSM is authorised.

Keywords: *deep sea mining, marine ecosystems, biodiversity loss, habitat destruction, sediment plumes, pelagic ecosystems, carbon sequestration, ecological risk, governance risk, precautionary governance*

1 Introduction

Terrestrial mining faces rising costs and growing environmental and social impacts, alongside declining access to high-grade deposits (Leyton-Flor & Sangha 2024; Myers 2025). Depletion is shifting production toward lower-grade and deeper resources that require more energy and entail higher rehabilitation expenditures, while resource independence and supply chain risks and uncertainty (Wang et al. 2025).

These pressures have led to renewed interest in marine minerals, with deep-sea mining (DSM) framed as an alternative supply pathway (He et al. 2026). However, DSM extends extraction into ecosystems that are more fragile, less understood, harder to regulate and far more difficult to rehabilitate than terrestrial systems. Rehabilitation, as used in this review, refers to repairing ecosystem functions (e.g. carbon cycling, basic biomass support) to a stable state, accepting that the original biodiversity may be lost (Tibbett 2024). In the deep sea, the mitigation hierarchy is constrained by weak baselines, unproven rehabilitation and non-credible like-for-like offsets (Tunnicliffe et al. 2025). One estimate of deep sea rehabilitation cost reaches up to USD75 million per hectare – rendering post-impact restoration economically prohibitive at any meaningful scale (Van Dover et al. 2014), and closure costing remains highly constrained (~AUD 108 million as of March 2026) (Petrossian & Lettieri 2024). With demand for critical minerals likely to make DSM a supplement rather than a substitute for terrestrial mining, biodiversity pressure and governance risk may compound, raising questions about the capacity of the International Seabed Authority (ISA) to regulate exploitation at scale (Tunnicliffe et al. 2025; Amon et al. 2022) (Figure 1).

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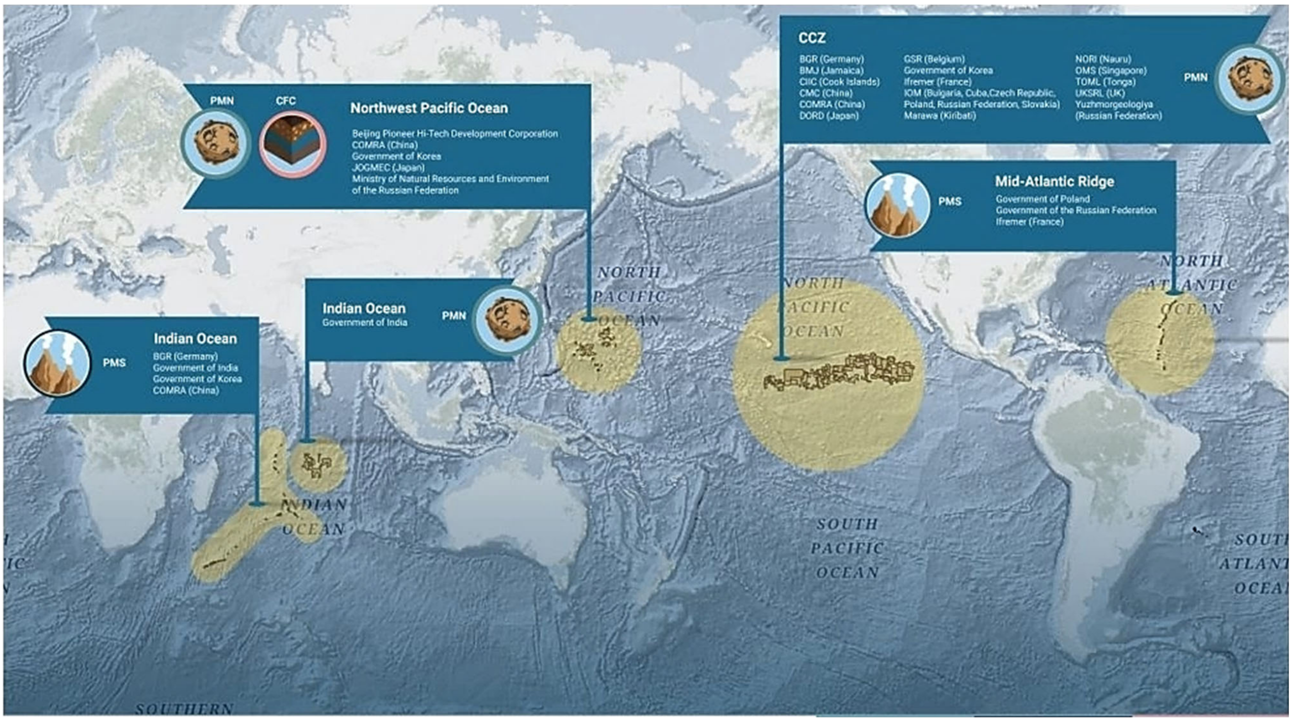

Figure 1 International Seabed Authority exploration contracts (n = 31; >1.3 million km²) by deposit type and region (adapted from International Seabed Authority, 2025)

An analysis of the 21 ISA-contracted states (Figure 1) found weak commitment to international conventions and moderate-to-high governance risk, raising doubts about the capacity to manage commercial-scale DSM responsibly (Petrossian & Lettieri 2024; Lubchenco & Haugan 2023; Pickens et al. 2023). Related legal materials examine liability for environmental harm, adaptive management obligations, investment protection and United Nations Convention on the Law of the Sea (UNCLOS)–human rights intersections (Craik 2020; Hamley 2022; Pecoraro 2019; Centre for International Governance Innovation 2018a; British Institute of International & Comparative Law 2023).

The deep sea remains one of Earth's least explored frontiers, hosting a multitude of communities adapted to darkness, cold temperatures, high pressure and low food availability. Major knowledge gaps persist in biodiversity, ecosystem function, connectivity and recovery from disturbance (Pickens et al. 2023; IUCN 2022; NOAA Ocean Exploration 2024).

This paper synthesises DSM environmental impacts through a rapid review of 60 sources (2016–2026), conducted in accordance with CEE guidelines (Collaboration for Environmental Evidence 2022) and reported using PRISMA 2020 (Page et al. 2021). It examines habitat disruption and biodiversity loss, sediment plumes, disruption of ocean carbon sequestration, pelagic/fisheries impacts and longer-term ecosystem alteration (Figure 2).

The review draws on peer-reviewed and grey literature, institutional reports and selected web-based sources and includes legal and policy analysis relevant to DSM governance and liability (Craik 2020; Centre for International Governance Innovation 2018a, 2018b; Pecoraro 2019; British Institute of International & Comparative Law 2023; Hamley 2022).

The IUCN 2022 defines DSM as the retrieval of mineral deposits from seabed areas below 200 m. High-value resources (e.g. gas hydrates, polymetallic nodules, cobalt-rich ferromanganese crusts and polymetallic sulphides) occur across ~360 million km² of deep sea floor (Miller et al. 2018).

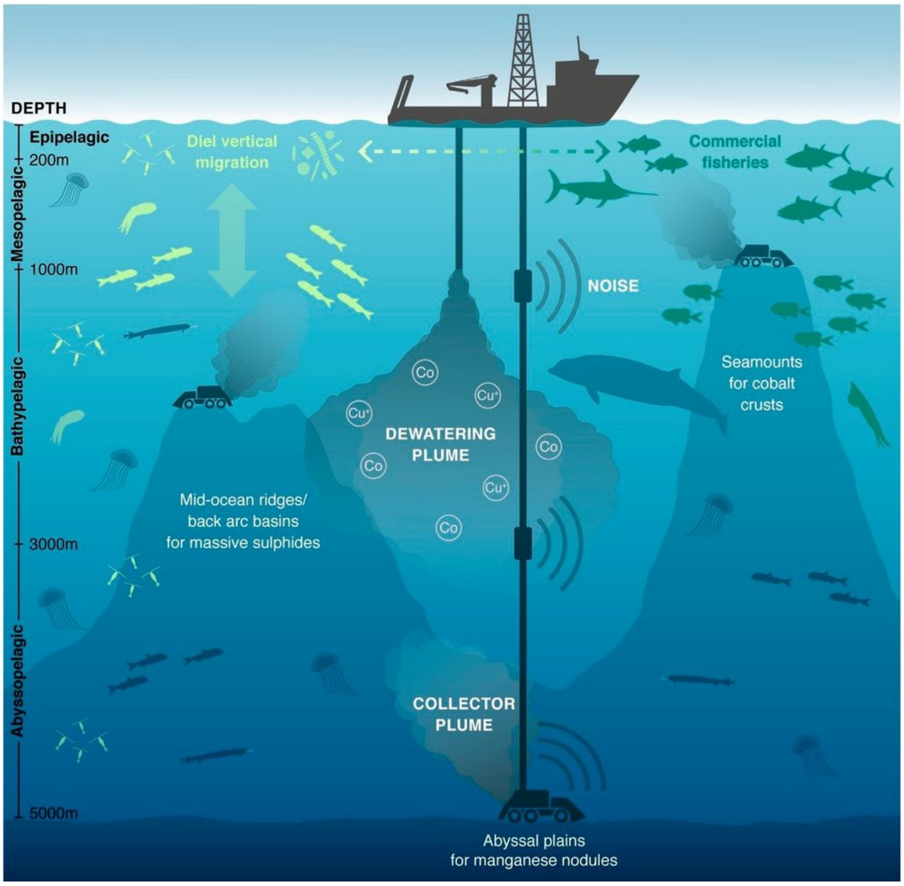

Figure 2 Polymetallic nodule mining system and key impact pathways (adapted from IUCN 2022)

1.1 Recent policy developments

Growing mineral demand has intensified interest in DSM and rapidly shifted the regulatory landscape. Reporting describes a Trump administration (2025–2026) push to accelerate U.S. involvement across international waters, federal jurisdictions and offshore Alaska, including streamlined rules intended to speed permitting and potentially trigger a U.S.-led race for seabed resources before global standards are settled (Alaska Beacon 2026; Hunnicutt 2026; National Oceanic and Atmospheric Administration 2026; Mining Reporters 2026).

National Oceanic and Atmospheric Administration (NOAA) has modernised the *Deep Seabed Hard Mineral Resources Act* permitting process by allowing a single consolidated application rather than separate exploration and commercial recovery permits (NOAA 2026; Perkins Coie 2026). While framed as supporting U.S. economic resilience, critics argue that environmental safeguards and technologies are not yet sufficiently mature (Deep Sea Conservation Coalition 2026).

Current research indicates that DSM poses a severe and unjustifiable risk: deep ocean ecosystems are highly vulnerable and poorly understood, technologies remain unproven and likely environmental and socio-ecological harms may outweigh potential benefits (Alam et al. 2025; Alger et al. 2025; Miller et al. 2018). These pathways may also transmit economic risk to coastal communities, insurers and investors (Alam et al. 2025), with further detail discussed in recent industry and policy commentary (Deep Sea Conservation Coalition 2026; Mining Reporters 2026; Perkins Coie 2026). Figure 3 illustrates the proposed footprint of NOAA's first DSM application.

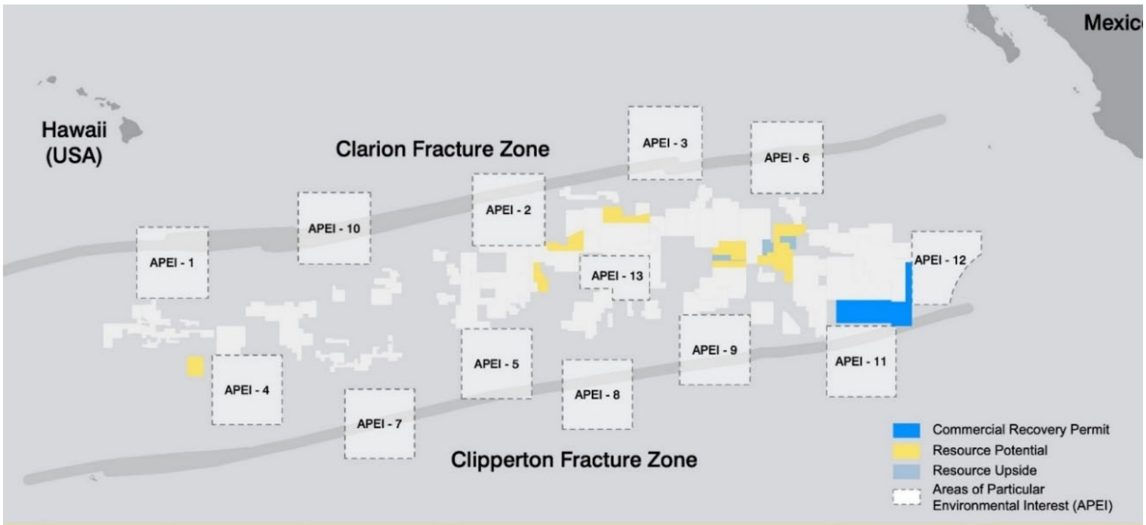

Figure 3 Initial National Oceanic and Atmospheric Administration deep sea mining application: proposed footprint and resource estimate (adapted from The Metals Company 2026)

In parallel, the U.S. Interior Department has sought industry interest in sea floor mining off Alaska, extending DSM policy beyond Areas Beyond National Jurisdiction (ABNJ) (Alaska Beacon 2026). Media reporting has also raised alleged ISA contractor non-compliance and oversight challenges, reinforcing the need for clear environmental and spatial baseline data for where a DSM operation is proposed. The next section summarises key provinces and jurisdictions (Oceanographic Magazine 2026).

2 Spatial distribution and location of deep sea mining operations

DSM operations occur across multiple ocean regions and target mineral deposits at depths of approximately 1,000–6,000 m. The Clarion–Clipperton Zone (CCZ) in the Pacific Ocean is the most prominent area of interest due to extensive polymetallic nodule fields. Other prospective provinces include mid-ocean ridges hosting polymetallic sulphide deposits associated with hydrothermal vents and seamounts with cobalt-rich ferromanganese crusts. Figures 4–6 illustrate the spatial distribution of DSM provinces, related governance contexts and the global distribution of hydrothermal vent fields (Lubchenco & Haugan 2023; Pickens et al. 2023).

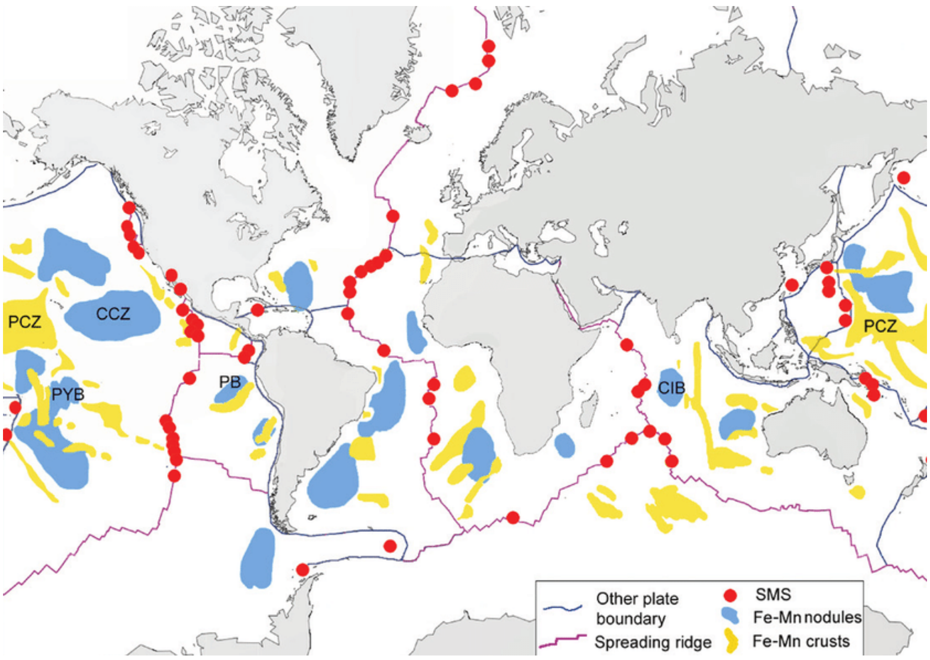

Figure 4 Major deep sea mining provinces associated with spreading ridges and plate boundaries (adapted from Hein et al. 2020)

Together, these spatial settings shape the types of habitats exposed to mining disturbance and the governance contexts in which impacts may occur. The next section outlines key environmental characteristics that influence ecosystem sensitivity and recovery.

3 Ecological characterisations of deep sea ecosystems

Deep sea ecosystems are defined by perpetual darkness below the photic zone (typically >200 m), near-freezing temperatures (approximately 2–4°C in abyssal zones) and extreme hydrostatic pressure (NOAA 2023; Andrade Daza 2024). These constraints have selected for highly specialised biota with slow growth, long lifespans, delayed maturity and low reproductive rates (Jones et al. 2020).

Polymetallic nodule provinces support diverse, often endemic benthic communities, with nodules providing essential hard substrate in otherwise soft-sediment habitats. Isolation, slow evolutionary rates and limited dispersal reduce genetic connectivity, increasing sensitivity to disturbance and prolonging recovery (Amon et al. 2016). Figure 5 summarises deep sea mineral formation processes for hydrothermal sulphides and abyssal nodules.

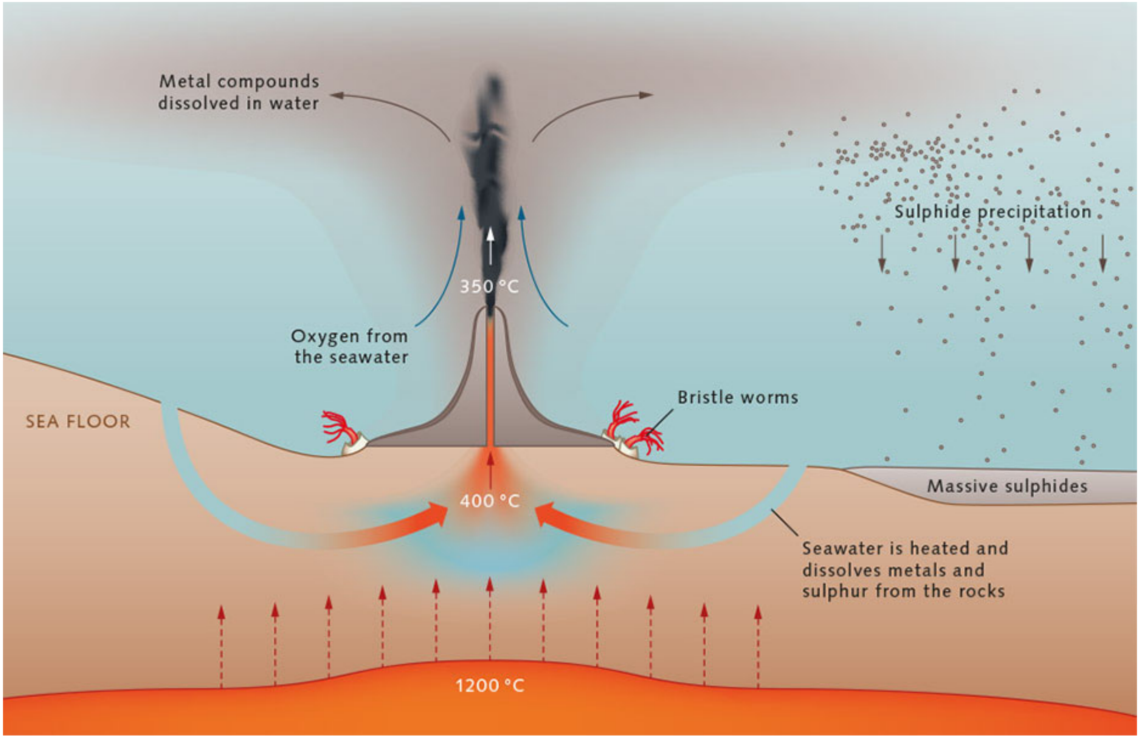

Figure 5 Deep sea mineral formation processes for hydrothermal sulphides and abyssal polymetallic nodules (adapted from World Ocean Review 2014)

4 Environmental risks and impacts of deep sea mining

DSM (Figure 2) is widely characterised as a significant and potentially irreversible threat to marine ecosystems (Petrossian & Lettieri 2024). Key impact pathways include seabed habitat removal, biodiversity loss, benthic and midwater sediment plumes, noise and vibration, artificial light and chemical releases. These stressors may disrupt food webs and biogeochemical cycling, weaken the biological pump and create downstream risks for fisheries-dependent communities (Amon et al. 2016; CSIRO 2022; Hein et al. 2020; Petrossian & Lettieri 2024).

Moreover, DSM remove substrate and benthic biota, compact and resuspend sediments, strip surface layers and eliminate habitat-forming substrates such as nodules, which support specialised communities (Amon et al. 2022). Recovery is likely to be extremely slow, potentially taking centuries to millennia, due to low biological productivity and slow nodule formation; disturbance experiments such as DISCOL show impacts can persist for decades with limited recolonisation (CSIRO 2022). Sediment plumes may extend beyond operational footprints, smother benthos and expose pelagic organisms, although their extent remains uncertain due to deep ocean circulation and limited monitoring (Hein et al. 2020). Combined with chemical contamination from spills, leaks, metal mobilisation and anoxic pore waters, and cumulative pressures from climate change, acidification and fishing, DSM increases the risk of long-term ecosystem change and fisheries impacts (Petrossian & Lettieri 2024). Figure 6 summarises the potential biodiversity impacts.

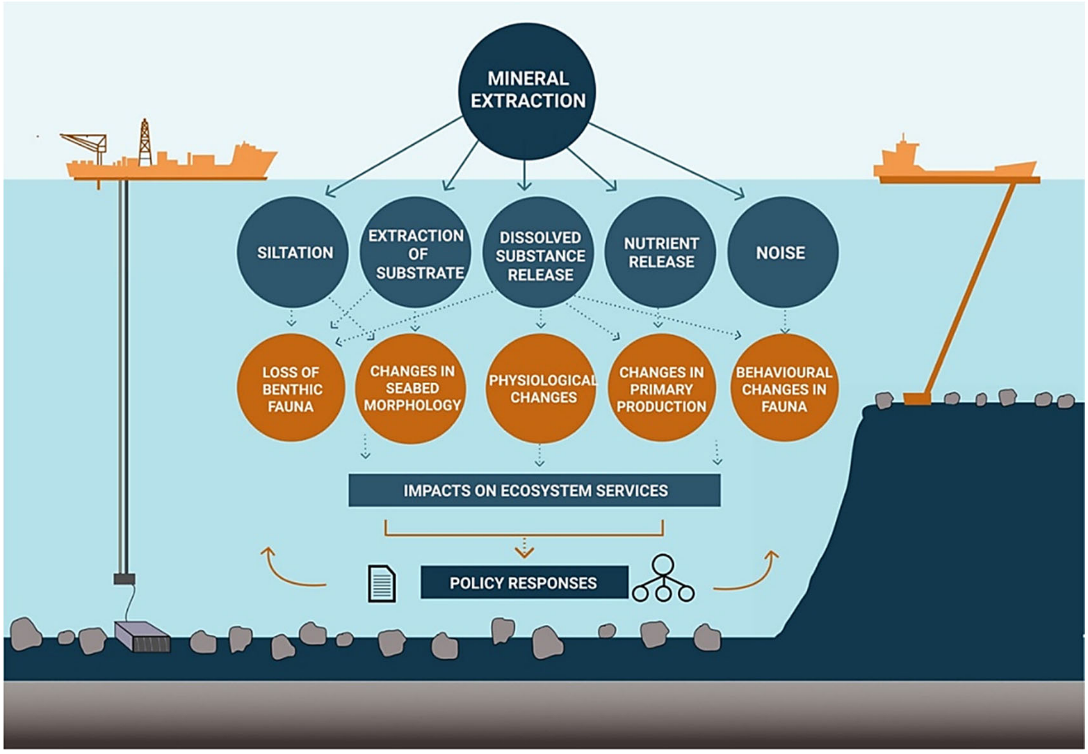

Figure 6 Potential impacts of deep sea mining on marine and coastal biodiversity (adapted from Kaikkonen et al. 2018)

4.1 Ecological risk synthesis: evidence from the legal literature

Legal sources broadly align with the ecological risk findings above. Fauna & Flora International (2023) concludes that the deep sea is highly biodiverse, interconnected and poorly understood, and identifies three compounding risks: current DSM technologies are unlikely to satisfy UNCLOS 'no serious harm' expectations; baseline data remain insufficient for reliable impact prediction; and biodiversity hotspots, including nodule fields, hydrothermal vents and seamounts, overlap with commercially attractive deposits. Singh & Jaeckel (2024) argue that these conditions undermine the legal sufficiency of authorising exploitation under UNCLOS, which requires 'effective protection' of the marine environment. Without binding thresholds, stop-rules, long-term monitoring and credible remedy pathways, particularly under cumulative pressures from climate change, acidification and fishing, DSM exploitation cannot be shown to meet this standard.

5 Methods

This rapid review used a structured, time-bound literature review approach consistent with core systematic review principles (*a priori* eligibility criteria, multi-source searching, explicit screening and reproducible synthesis). To maintain feasibility within a 6-week timeframe, justified accelerations were applied (narrowed database coverage and single-reviewer extraction with verification). Evidence sources included peer-reviewed scientific and legal literature, government and intergovernmental reports, grey literature and web-based institutional and advocacy materials.

The review follows Environmental Evidence rapid review criteria and ROSES reporting standards (Haddaway et al. 2020) and is consistent with methods described by Mengist et al. (2020), Duarte-Kzam et al. (2025) and Snyder (2019).

5.1 Review question

The review addresses the overarching question regarding what the current literature reveals about the environmental impacts, regulatory frameworks, governance challenges and social legitimacy of DSM.

Sub-questions address ecological risks (biodiversity loss, habitat destruction, sediment plumes, pelagic impacts and carbon sequestration); governance and regulatory challenges (UNCLOS, ISA and precautionary governance); closure and rehabilitation obligations; and terrestrial mining as a comparator for disturbance and recovery.

5.2 Search strategy

Literature searching was undertaken during a 6-week rapid review (13 January–21 February 2026), with additional time allocated to screening, extraction, synthesis and write-up. Searches and screening were completed by the author using streamlined rapid review procedures to retain transparency and reproducibility while applying clearly justified shortcuts (Devane et al. 2024).

Search strings used Boolean operators targeting DSM regulation and governance, environmental impacts, benthic ecosystems, closure and rehabilitation, UNCLOS/ISA accountability, investment arbitration, the BBNJ Agreement and enforcement.

5.2.1 Keywords and conceptual clusters

Keywords were grouped into 3 conceptual clusters (Table 1) and combined in Boolean strings, using variants and truncations to maximise recall while retaining precision.

Table 1 Search keywords and conceptual clusters

Cluster	Primary keywords	Variant/related terms	Databases/sources searched
A – Ecological & environmental impacts	deep sea mining, marine ecosystems, biodiversity, habitat disturbance, sediment plumes, pelagic impacts, carbon sequestration	benthic habitat, plume dispersion/modelling, deep sea ecology, carbon cycling, ecosystem services, megafauna	Scopus; Web of Science; Google Scholar; Deep Sea Conservation Coalition; NOAA/CSIRO portals
B – Governance & regulatory frameworks	governance, regulation, precautionary principle	adaptive management, ISA, UNCLOS/BBNJ, EIA, liability/accountability, stakeholder participation, investment arbitration, enforcement, moratorium/pause	Scopus; Web of Science; Google Scholar; ISA; UN/UNCLOS Ocean Atlas; Deep Sea Conservation Coalition
C – Mine closure, rehabilitation & terrestrial comparators	mine closure, rehabilitation, remediation, terrestrial mining comparator	decommissioning, post-mining recovery, rehabilitation, care and maintenance, reclamation, DSM enforcement	Scopus; Web of Science; Google Scholar; ISA; NOAA/CSIRO portals

Within-cluster terms were combined using 'OR' and clusters were combined using 'AND' to ensure each record related to DSM and at least one thematic domain. Where character limits applied, Cluster A terms were prioritised.

5.2.2 Databases and sources searched

Searches were conducted across academic databases and targeted institutional and grey literature sources; Table 2 summarises sources searched and the keyword clusters applied.

This review applies targeted search strings and *a priori* eligibility criteria to identify literature most relevant to DSM environmental governance, ecological risk and regulatory frameworks. The search returned 312 records, of which 60 met inclusion criteria and were synthesised.

5.3 Eligibility criteria and screening

Eligibility criteria were defined *a priori* and applied at title/abstract and full text screening. Included sources comprised peer-reviewed publications, books/chapters, institutional/government reports, policy analyses and substantive NGO materials; criteria are summarised below:

- Language: English only.
- Date range: 2016–2026 primary window; older seminal works included where necessary.
- Topic relevance: DSM plus ≥1 review keyword (exclude incidental DSM mentions; shallow water dredging without DSM focus; terrestrial mining without DSM comparison).
- Source type: peer-reviewed articles; books/chapters; institutional/government reports; policy analyses; substantive NGO materials; and conference proceedings (exclude blogs, opinion pieces, social media, Wikipedia and abstract-only records where full text cannot be obtained).
- Geographic scope: any jurisdiction.
- Accessibility: full text available via institutional access, open access, or author copy.

Records were screened in 3 stages (title, abstract, full text). From 312 retrieved records, duplicates were removed and 60 sources were included in the qualitative synthesis. The PRISMA 2020 flow diagram is provided in Figure 7.

5.4 Quality and relevance appraisal

A bespoke, fit-for-purpose appraisal rubric was applied to support transparent evidence weighting across mixed study types. Each source was assessed against the following domains:

- Internal validity/credibility: methods, transparency, data quality and coherence of claims with supporting evidence.
- External applicability: relevance to DSM contexts, transferability and temporal currency.
- Quality of legal reasoning (where applicable): use of primary authorities, interpretive rigour and acknowledgement of counterarguments.
- Risk of bias**:** conflicts of interest, advocacy positioning and selective reporting.

5.5 Limitations

As a single-author rapid review conducted over ~6 weeks (13 January–21 February 2026), this study necessarily traded breadth for timeliness. Consequently, time compression and streamlined procedures may reduce methodological breadth/rigour relative to a full systematic review and can increase bias risk if shortcuts are not transparent (Ganann et al. 2010; Moons et al. 2021; Devane et al. 2024).

Terrestrial mining keywords were used as a comparator framework; sources without explicit DSM relevance were excluded, which may limit closure/rehabilitation benchmarking. Nonetheless, a rich source of peer-reviewed, institutional and grey literature supports robust identification of patterns and gaps in DSM environmental governance.

6 Results

6.1 Thematic frequency across the literature corpus

Table 2 reports the frequency of coded themes across included sources (n = 60), as counts and percentages. Figures 8–10 visualise publication counts by year and proportional thematic distribution. Sources could be coded to multiple themes.

Grey literature includes NGO and policy brief materials (e.g. Deep Sea Conservation Coalition 2023, 2026; Deep Sea Mining Campaign 2021) and technical reports (e.g. Fauna & Flora International 2023). A small number of web-based sources captured fast-moving policy developments during 2025–2026.

Table 2 Thematic frequencies across the included literature (n = 60)

Theme	Count (n)	Proportion of corpus	Primary source categories
Environmental impacts	18	30.0%	Government/institutional, peer-reviewed, web-based
Governance frameworks	17	28.3%	Across all source categories
Social & economic impacts	8	13.3%	Grey literature, peer-reviewed, web-based
Marine ecosystems	6	10.0%	Peer-reviewed, government/institutional, web-based
Biodiversity conservation	5	8.3%	Peer-reviewed, web-based
Technological challenges	3	5.0%	Peer-reviewed, grey literature
Rare earth elements	3	5.0%	Peer-reviewed, government/institutional
Total	**60**	**100%**	

Counts corrected from source document (original total was 60); 3 previously uncoded sources have been assigned to Environmental impacts, Governance frameworks, and Social & economic impacts, respectively, bringing the coded total to 60. Sources may be coded to more than one theme; counts and percentages are therefore not mutually exclusive.

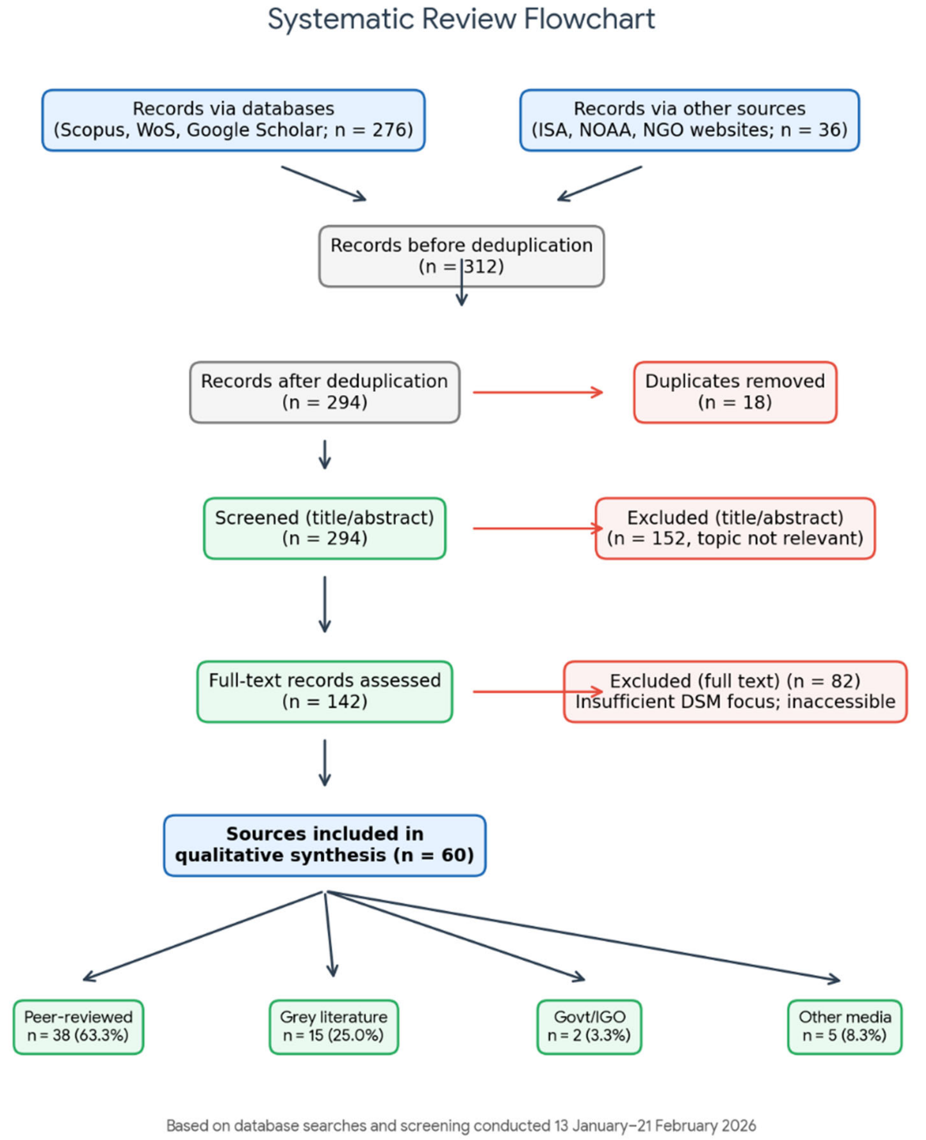

Figure 7 PRISMA 2020 flow diagram of study screening and inclusion

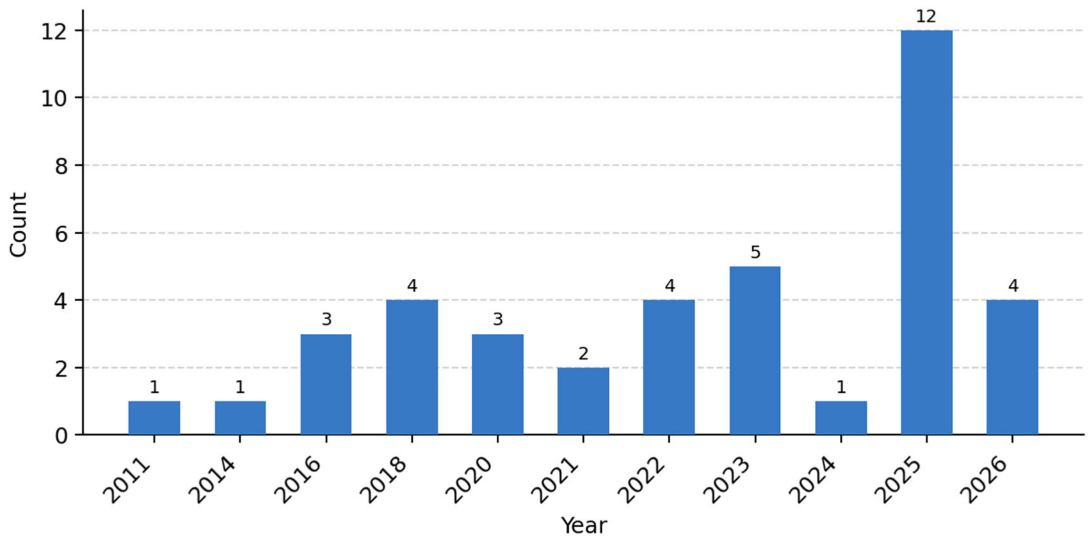

Figure 8 Publication counts by year for included sources (2011–2026)

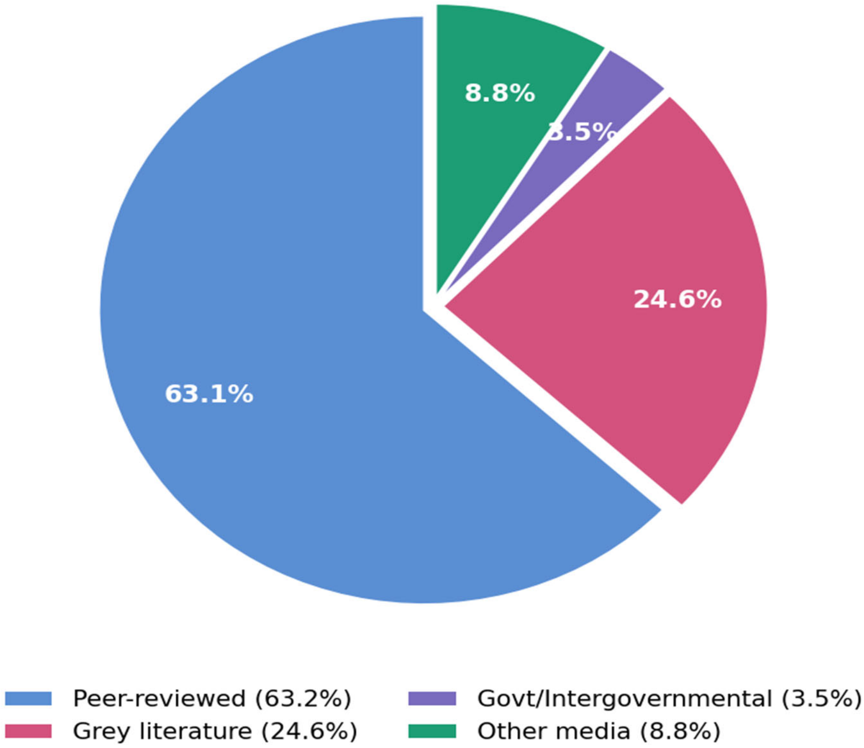

Figure 9 Distribution of included sources by evidence class (n = 60)

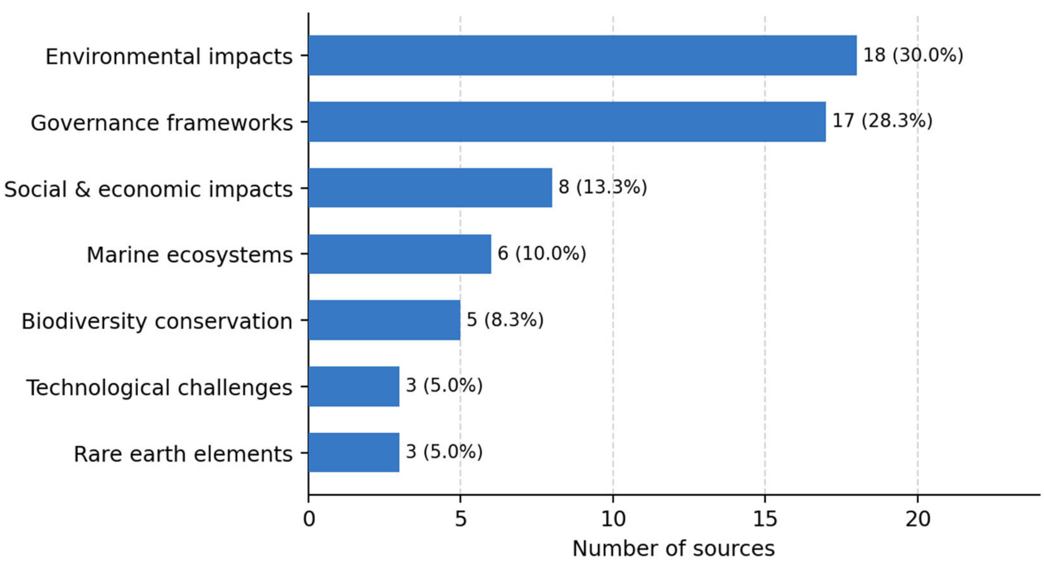

Figure 10 Overall thematic distribution across the included literature (n = 60)

Table 3 Representative sources included in the review

Citation	Focus	Method	Key finding	Themes
Alam et al. (2025)	Downstream social-ecological and economic risks	Simulation analysis	Maps impact pathways and economic exposure	SE, G
Alger et al. (2025)	DSM ‘necessity’ and legitimacy under uncertainty	Policy analysis	Benefits uncertain; governance limits weaken ‘necessity’ claims	G, E
Amon et al. (2022)	Is DSM needed? Policy implications	Perspective	Challenges necessity; highlights uncertainty and exploitation stage risk	G, E
Miller et al. (2018)	DSM resources, risks and research needs	Review/synthesis	Synthesises knowledge gaps; cautions on vulnerability and governance readiness	E, ME, G
Petrossian & Lettieri 2024	Governance capacity of ISA-contracted states	Comparative assessment	Finds governance risk and uneven treaty ratification; notes rehabilitation costs and enforcement limits	G, E
Hein et al. (2020)	Sediment plumes and impact pathways	Synthesis/modelling	Plume extent uncertain; impacts may extend beyond mine footprints	E, ME
Guo et al. (2023)	Plume dispersion and exposure uncertainty	Modelling	Plume impacts hard to predict and potentially widespread	E, ME
Kaikkonen et al. (2018)	Biodiversity and ecosystem impact pathways	Synthesis/review	Summarises biodiversity and ecosystem impact pathways for management and monitoring	E, BC, ME
IUCN 2022	DSM overview and key environmental concerns	Issues brief	Summarises key risk pathways and governance concerns	E, G
NOAA (2025)	DSM risks and uncertainty (state of the science)	Fact sheet	Emphasises data gaps, uncertainty and need for caution	E, G

Note. Theme codes: E = environmental impacts; G = governance frameworks; SE = social & economic impacts; ME = marine ecosystems; BC = biodiversity conservation; TC = technological challenges; REE = rare earth elements. Full literature grid available on request.

7 Regulatory frameworks and governance context

Effective management of DSM requires coherent regulation at international, regional and national scales. In Areas Beyond National Jurisdiction (ABNJ), the International Seabed Authority (ISA), established under the United Nations Convention on the Law of the Sea (UNCLOS), is the principal regulator. A fuller discussion of legal and approval pathways is provided in the companion paper *Legal Perspectives on Seabed Mining: Regulatory Frameworks & Governance in Australian & International Contexts* (Ashby 2026).

Petrossian & Lettieri (2024) assessed the 21 ISA-contracted states against ratification of 17 international conventions and 18 governance risk indicators (e.g. corruption, rule of law, political stability, regulatory quality). Most states showed weak or inconsistent treaty ratification and moderate-to-high governance risk, raising concerns about oversight and compliance capacity. The study also notes that deep-sea rehabilitation remains unproven and potentially prohibitive (up to USD 75 million per hectare) (Petrossian & Lettieri 2024).

7.1 Environmental impact assessment deficiencies and the evidence–regulation gap

Independent analyses conclude the ISA's environmental impact assessment (EIA) regime is not yet fit for exploitation stage decisions, citing unclear risk standards, weak alternatives analysis, limited participation and inadequate cumulative-impact requirements. Proposed reforms include quantitative risk modelling, explicit thresholds and stop-rules, enforceable cumulative-impact assessment and stronger remedies to support accountability (Frontiers in Ocean Sustainability 2024; Frontiers in Marine Science Editorial Team 2025).

Recurring impact pathways (benthic disturbance, plumes, noise/light, toxic releases and cumulative pressures) imply the following minimum governance requirements:

1. adequate baselines and reference zones
2. explicit thresholds, triggers and stop-rules aligned with UNCLOS 'effective protection/no serious harm'
3. cumulative-impact assessment at relevant scales
4. independent verification, transparency and enforceable adaptive management
5. closure and post-closure monitoring backed by financial assurance.

These elements remain only partly reflected in the ISA Mining Code, sustaining an evidence–regulation gap (Frontiers in Ocean Sustainability 2024; Frontiers in Marine Science Editorial Team 2025).

Oztig (2025) reviews 45 social science articles on DSM (2018–2024) and finds international relations scholarship is largely absent despite DSM's geopolitical stakes (resource access, benefit-sharing and political economy). The review argues legitimacy conditions – participation, equitable benefit-sharing, geopolitical fairness and interdisciplinary governance – remain underdeveloped alongside scientific prerequisites for safe exploitation.

7.2 Translating land-based mining regulatory processes to the deep sea context

Squillace (2021) argues regulatory process design – rather than geology – largely determines environmental outcomes, making land-based mining governance a useful template for DSM. The U.S. *Surface Mining Control & Reclamation Act* (SMCRA 1977) illustrates safeguards including independent enforcement, detailed permitting, full-cost financial assurance, enforceable performance standards and regular inspections.

For an emerging sector, Christiansen & Bräger (2023) argue that best environmental practice (BEP) must be inferred from research, disturbance experiments and analogous industries. Xu, Li & Xue 2023 likewise note the ISA's draft Exploitation Regulations reference best available techniques (BATs) and BEP but do not define or operationalise either. A Western Australian case study demonstrates how weak closure safeguards generate deferred liability. Ashby, van Etten and Lund (2016) found that inadequate bonding and absent statutory time limits allow care-and-maintenance to persist with minimal rehabilitation—where only 3 of 20 sites exceeded 70% across assessed domains—leaving ongoing environmental risks like compromised tailings, contaminated pit lakes, and eroding waste rock landforms. This pattern extends directly to abandoned and legacy operations, where unclear statutory obligations enable environmental harm to accumulate until rehabilitation costs are externalised to the public sector. Ashby (in press) identifies this regulatory gap as a structural flaw in mining governance, drawing an explicit link between terrestrial frameworks and international regimes to show how operators exploit legal vacancies to defer obligations while liabilities grow.

This terrestrial failure directly mirrors emerging Deep Sea Mining (DSM) risk: where institutional capacity is restricted and offshore closure frameworks remain underdeveloped, extraction proceeds while environmental responsibilities are postponed, ultimately transferring long-term liability to sponsoring states or, in the 'Area', the global commons (Petrossian & Lettieri 2024). Consequently, this parallel underscores the necessity of embedding enforceable closure and post-closure stewardship requirements directly into the International Seabed Authority (ISA) exploitation regime. Mitigating this risk requires transparent operational standards, independently verified environmental monitoring, and SMCRA-style full-cost financial assurance to completely block liability transfers if private operators default.

In Australia's domestic context, the contrast with ISA processes is pronounced. The *Environment Protection & Biodiversity Conservation Act 1999* (Cth) (EPBC Act) sets comparatively strong assessment expectations (including cumulative impacts and participation), and reforms under the *Environment Protection Reform Act 2025* (Cth) further raise standards through National Environmental Standards, an 'unacceptable impacts' test, restoration charges in place of offsets and stronger compliance powers (Parliament of Australia 2025; DCCEEW 2026).

With Tranche 1 commencing on 20 February 2026 and the National Environmental Protection Agency commencing on 1 July 2026, this divergence creates a credibility challenge for Australia as an ISA member and potential sponsoring state and strengthens the case for advocating mandatory cumulative-impact assessment, enforceable thresholds/stop-rules and improved transparency and participation within ISA negotiations.

8 Environmental monitoring and impact mitigation

Given the magnitude and potential irreversibility of DSM impacts, monitoring and adaptive management must be built around robust baselines capable of detecting mining-attributable change. Baseline assessments should characterise pre-mining conditions at adequate spatial and temporal resolution, and regional environmental management plans (REMPs) should designate preservation and impact reference zones and areas of environmental interest to maintain connectivity and protect representative habitats (International Seabed Authority 2023). Mitigation should prioritise avoidance and footprint minimisation, with plume management supported by optimised discharge depths and collector design; real-time systems (e.g. autonomous underwater vehicles, benthic landers, acoustic arrays) can track key parameters, although effectiveness at commercial scale remains unproven.

Monitoring and mitigation must also be integrated with closure governance, which remains underdeveloped in DSM regulation despite its direct link to long-duration recovery and liability. The 2016–2026 literature converges that exploitation is not credibly authorisable without binding closure and post-closure obligations, independently verified monitoring and financial assurance sufficient for long-duration stewardship and remediation if operators' default (Singh et al. 2025). Precautionary tools (pauses, moratoria, staged approvals) are increasingly treated as functional closure measures where end-states and remedies cannot yet be demonstrated (Singh & Jaeckel 2024). A stewardship approach frames authorisation, monitoring and closure as a continuum rather than discrete project stages, potentially supported by strengthened scientific advisory capacity and multi-decadal planning that explicitly accommodates uncertainty and environmental variability (Graydon 2023; Rosenbaum & Sharma 2023; Levin et al. 2020).

9 Knowledge gaps and research priorities

Substantial knowledge gaps constrain the prediction, regulation and management of DSM impacts. Many deep-sea taxa remain undescribed and poorly mapped, and relationships among biodiversity, ecosystem processes and services are incompletely understood, limiting impact assessment. Recovery trajectories are also poorly constrained due to scarce long-term empirical data from disturbance experiments.

Priority research needs include comprehensive biodiversity surveys; long-term monitoring of experimental and legacy disturbance sites; improved sediment plume modelling validated against in situ observations; connectivity studies integrating genetics with physical oceanography; and experiments on organism-level responses to key stressors (sedimentation, noise and metal exposure).

A critical unresolved gap concerns whether abyssal rehabilitation is feasible at all. No peer-reviewed studies from 2025–2026 provide updated deep-sea per-hectare rehabilitation costs; recent quantitative figures largely come from shallow systems and are not transferable (e.g. coral reef restoration costs of USD 10,000–226 million per hectare; median USD 558,000 for coral gardening) (Mulà, Bradshaw & Strona 2025). The DEEP REST project reported no observable recovery and suggested restoration, if possible, may require 100–1,000 years (Gollner et al. 2025). Planet Tracker 2023 estimates USD 5.3–5.7 million per km² (~USD 53,000–57,000 per hectare) for artificial nodule seeding scenarios, but this does not recreate complex biogenic habitats. Accordingly, the most relevant deep sea scenario estimate remains USD 75 million per hectare (Van Dover et al. 2014; USD 2013) (≈AUD 108 million) (Petrossian & Lettieri 2024). Overall, feasibility – not cost – is the binding constraint: extreme uncertainty and absent demonstrated recovery mean rehabilitation is not a credible offset, reinforcing the need for precautionary decision-making.

10 Conclusion

This rapid review of 60 sources demonstrates that DSM poses substantial and potentially irreversible threats to marine ecosystems across multiple, well-documented pathways, including habitat destruction, biodiversity loss, sediment plume generation, chemical and acoustic pollution and ecosystem-level change. The defining characteristics of deep sea environments extreme physico-chemical conditions, slow biological processes, high endemism and limited connectivity produce exceptionally low resilience to disturbance. Consequently, commercial-scale extraction is likely to generate impacts that are severe, spatially extensive and persistent over long timescales.

The evidence indicates that ecological recovery, where possible, is likely to require centuries to millennia. Major knowledge gaps in deep sea biodiversity, ecosystem function, connectivity and recovery create profound uncertainty for impact prediction and management. These uncertainties reinforce the need for comprehensive baselines, advanced and independently verified monitoring, precautionary governance and enforceable mitigation and stop-rules responsive to early signs of irreversible harm.

Governance risk compounds these environmental uncertainties. Petrossian & Lettieri (2024) report that most states sponsoring or holding ISA exploration contracts exhibit weak treaty compliance and moderate-to-high governance risk, raising doubts about institutional capacity to prevent, detect or remediate harm in practice. Combined with irreversible-loss risks, unproven rehabilitation feasibility and rehabilitation cost estimates up to USD75 million per hectare, these deficits undermine claims that environmental protection obligations can be met under current settings.

Taken together, the evidence supports a clear conclusion: commercial-scale DSM should not proceed without robust, independently verified governance, regionally representative baseline data, enforceable environmental thresholds, demonstrably effective mitigation and binding closure and liability mechanisms capable of addressing long-term harm. Until these conditions are met, a strongly precautionary approach – including restraints on authorisation – remains the only scientifically and legally defensible pathway for managing deep sea mineral resources in the global commons.

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