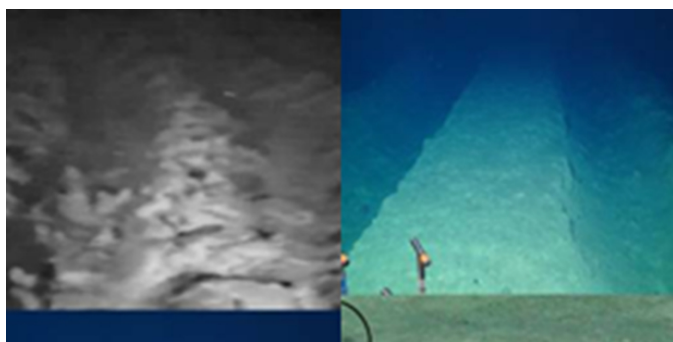


national Seabed Area (hereinafter "the Area"). The total quantity of nodules on the ocean floor is estimated at approximately 500,000 million tonnes, with the Clarion - Clipperton Zone (CCZ) representing the highest known concentration (Zhang et al., 2024). Recent prospections have expanded the perimeter of interest, documenting nodules on seamount flanks, which complicates both environmental management and the applicable regulatory framework (Du Preez et al., 2025).

Deep-sea mining (DSM) is posited as a solution to the critical minerals deficit (Macchi, 2025). However, this activity operates in ecosystems characterised by extreme conditions and fragile biodiversity whose recovery capacities are practically negligible on human timescales (Jones et al., 2025; Du Preez et al., 2025). As shown in Figure 1, the tracks produced during the 1979 OMCO mining test remain visible in 2023. The asymmetry between short-term economic incentives and long-term ecological risks constitutes the core dilemma addressed by this article.

Figure 1: Tracks from the 1979 OMCO mining test, photographed in 2023.



Source: <https://doi.org/10.1038/s41586-025-08921-3>.

An additional source of geopolitical pressure is the competition among major powers for control of critical mineral supply chains. China holds five ISA exploration contracts, more than any other country, and has concluded agreements with small island states, including the Cook Islands, for joint studies (CSIS, 2025). Against this backdrop, the Trump administration signed, on 24 April 2025, the Executive Order entitled Unleashing America's Offshore Critical Minerals and Resources, instructing NOAA and the Bureau of Ocean Energy Management (BOEM) to expedite exploration licences and commercial exploitation permits, including areas beyond United States national jurisdiction (Greenpeace USA, 2025; CSIS, 2025). This unilateral action, characterized by ISA Secretary-General Leticia Reis de Carvalho as a violation of international law, has fractured multilateral consensus on DSM governance and introduced unprecedented legal uncertainty (ISA, 2025b; Inside Climate News, 2025).

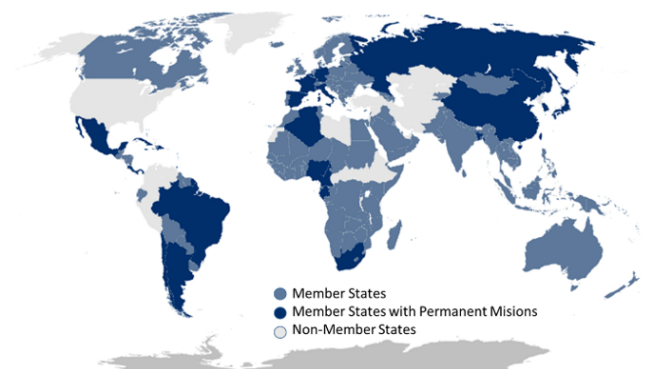
1.1. The International Legal Framework: UNCLOS and the ISA.

The governance of the Area is regulated by the United Nations Convention on the Law of the Sea (UNCLOS), adopted

in 1982 and in force since 1994 (Freestone, 2011). Part XI enshrines the principle of the "common heritage of mankind," implying that no State or private entity may claim sovereignty over the Area's resources or exploit them unilaterally, and that the benefits must be equitably shared (UNCLOS, Arts. 136–137; Freestone, 2011). This principle was refined by the 1994 Implementation Agreement to facilitate accession by industrialised countries (Singh, 2022).

The ISA currently comprises 171 States Parties and the European Union (Figure 2) (Singh, 2022; Blanchard et al., 2023), and has concluded 31 exploration contracts covering 1.5 million km² of ocean floor (Pickens et al., 2023; Blanchard et al., 2023). The Legal and Technical Commission (LTC) commenced drafting the Mining Code for exploitation in 2019. However, Pickens et al. (2023) identified more than thirty substantive unresolved regulatory issues, attributable to insufficient deliberation time, divergence of interests, and the absence of consolidated scientific information.

Figure 2: ISA Member States.



Source: <https://isa.org.jm/member-states/>.

1.2. The Regulatory Crisis: The Two-Year Rule and 2025 Developments.

In June 2021, Nauru invoked Section 1(15) of the Annex to the 1994 Agreement (the two-year rule"), notifying the ISA of the intention of Nauru Ocean Resources Inc. (NORI, a subsidiary of The Metals Company, hereinafter TMC) to submit an exploitation plan (Singh, 2022). The Council was thereby obliged either to complete the Regulations, Recommendations and Procedures (RRPs) within two years or, provisionally consider any application submitted in the absence of a definitive code (Singh, 2022; Willaert, 2021).

The deadline elapsed on 9 July 2023 without adoption of the RRP. Part I of the ISA's 30th Session (March 2025) completed the second reading of Articles 1 to 55 of the consolidated text of the regulations. Part II (7–25 July 2025) concluded the reading of Articles 56 to 107, advancing provisions on marine environment protection, inspection mechanism, and fiscal equalisation measures designed to ensure that the effective DSM tax rate matches terrestrial mining (Earth Negotiations Bulletin, 2025). However, the Mining Code was not adopted, and no binding timetable was established. During the Assembly, Croatia joining 38 countries supporting a moratorium, pause, or prohibition

on DSM (Seas at Risk, 2025).

Concurrently, TMC's United States subsidiary attempted to obtain permits from NOAA under the 1980 Deep Seabed Hard Mineral Resources Act (DSHMRA), which was unanimously rejected by ISA members, who agreed to investigate potential violations (Seas at Risk, 2025; DLA Piper, 2025a). Secretary-General Carvalho stated categorically that no State has the right to unilaterally exploit the Area outside UNCLOS (ISA, 2025b). This tension renders negotiations of uncertain duration (Pickens et al., 2023; DLA Piper, 2025b).

1.3. Documented Environmental Impacts.

Scientific evidence demonstrates that nodule extraction generates at least four categories of potentially irreversible ecological disturbance:

Direct destruction of benthic habitat: The DISCOL experiment (1989) and its 26-year follow-up studies demonstrate that benthic communities failed to recover statistically significant taxonomic composition or biomass relative to reference areas (Jones et al., 2025). A sediment plume generated during European Union trials (2021) in the CCZ travelled more than 4 km from its origin, blanketed organisms, and reached particle concentrations up to 100 times above baseline values (Haeckel et al., 2024, as cited in PMC 2024).

Large-scale sediment plumes: A pre-prototype collection trial at 4,500 m depth revealed that the benthic plume formed a gravity current travelling 500 m downslope, while suspended particles reached up to four orders of magnitude above ambient reference values (Gillard et al., 2025).

Mesopelagic zone impacts: Research from the University of Hawaii documented that DSM waste discharge generates physiological stress in mesopelagic zooplankton (twilight zone, 200–1,000 m), disrupting trophic networks and the biological carbon pump (University of Hawaii at Manoa, 2025).

Acoustic and seamount perturbation: Broadband underwater noise (Martin et al., 2021) and the disruption of seamount ecosystems require urgent revision of Regional Environmental Management Plans (REMPs), which are currently designed only for abyssal plains (Du Preez et al., 2025).

1.4. Methodology, Objectives, and Structure.

This article integrates three complementary methodologies: a legal-normative analysis of UNCLOS's architecture and the Mining Code drafting process through July 2025; a technical-scientific review evaluating extraction, monitoring, and mitigation technologies published between 2021 and 2025; and a multilevel governance synthesis examining the articulation between the ISA regime, the BBNJ Agreement, and national frameworks.

This article advances existing literature by providing an integrated law-technology-governance assessment updated to July 2025, incorporating the consequences of the April 2025 Trump Executive Order as a systemic inflection point. Unlike Macchi (2025), who focuses on corporate due diligence, this article critically evaluates the technology-regulation gap and the 2025 geopolitical fracture as a rupture of multilateral consensus

The analysis rests on four systematic concepts:

- The Precautionary Principle (Rio Declaration, Principle 15; UNCLOS, Art. 145), placing the burden of proof on proponents of exploitation.
- The Governance of Global Commons (Ostrom, 1990; Freestone, 2011), requiring institutional monitoring, graduated sanctions, and dispute resolution mechanisms.
- Regulatory Lag Theory (Collingridge, 1980; Marchetti, 2022), describing the tendency of normative frameworks to fall behind technological progress.
- The Accountability Gap (Macchi, 2025; Theil & Rahbar, 2024), denoting the gulf between a private actor's capacity to cause harm and available liability mechanisms.
- These concepts converge on the central conclusion: the current governance of DSM is structurally incapable of ensuring the protection of abyssal ecosystems under commercial pressure.

2. Normative Framework and Governance Challenges.

2.1. The UNCLOS Normative Architecture and the Mining Code.

The normative architecture governing the Area rests on three levels: UNCLOS articles establishing the common heritage principle; binding Regulations, Recommendations and Procedures (RRPs); and non-binding subsidiary standards and guidelines (Pickens et al., 2023). While exploration RRP were adopted between 2000 and 2012, the exploitation code remains incomplete due to deep substantive disagreements over the economic model, environmental protection levels, and benefit distribution (Pickens et al., 2023).

During Part II of the 30th Session (July 2025), the Council completed the second reading of all 107 articles of the consolidated text. Despite concrete progress on the inspection, compliance, and enforcement (ICE) mechanism, including a new Compliance Committee, environmental impact assessments - (EIA), and fiscal equalisation measures, critical issues remained unresolved. Disputes persisted regarding effective contractor control, underwater cultural heritage, and the specific mechanics of fiscal equalisation, leaving the Mining Code unadopted and without a binding calendar for 2026 (Earth Negotiations Bulletin, 2025; IISD, 2025).

2.2. State Responsibility, Due Diligence, and Ethical Gaps.

Sponsoring State responsibility is governed by UNCLOS Article 153(4) and Annex III. The 2011 ITLOS Advisory Opinion clarified that this is an obligation of conduct, not of result, requiring States to adopt appropriate national measures without incurring strict liability (Freestone, 2011). However, Macchi (2025) demonstrates that these due diligence obligations are structurally insufficient due to the absence of binding environmental standards, public disclosure requirements, and accountability mechanisms for transboundary harm, creating an accountability gap for contractors with prior operational risks (Theil & Rahbar, 2024).

The case of TMC illustrates this problem. The company, publicly listed since 2021 with shares fluctuating following the Trump administration support, has sponsored trials in the CCZ while accumulating losses, pushing commercial prospects to late 2027 (Grist, 2025). TMC's corporate structure, utilizing subsidiaries sponsored by Pacific micro - states like Nauru and Tonga with limited technical supervisory capacity, exemplifies the risk of "flags of convenience" in DSM (Macchi, 2025). Although 2025 RRP drafts incorporate an "effective control" requirement, persistent ambiguity remains over whether the criterion should be regulatory, operational, or capital - based, threatening "forum shopping" across permissive jurisdictions (Vinson & Elkins, 2024; DSCC, 2025).

2.3. *The Environmental Compensation Fund and Reparatory Architecture.*

Article 22 of Annex III of UNCLOS provides for liability for damage caused in the Area, but establishes no specific reparatory mechanism. Wang et al. (2025) analysed the Environmental Compensation Fund (ECF) incorporated in the 2025 draft RRP (Regulation 55), concluding that critical deficiencies persist. Liability is limited to "actual damage incurred," excluding diffuse, transboundary, or cumulative harm, the precise impacts most likely to arise from commercial-scale DSM. Furthermore, compensation mechanisms must be harmonised with the EIA process and continuous monitoring frameworks, requiring a systemic coherence that the current draft fails to guarantee (Wang et al., 2025).

2.4. *The 2025 Geopolitical Fracture: The United States Executive Order.*

On 24 April 2025, the Trump administration signed the Executive Order Unleashing America's Offshore Critical Minerals and Resources, instructing NOAA and BOEM to expedite seabed exploration and exploitation permits within the Area under the 1980 DSHMRA (Greenpeace USA, 2025; Inside Climate News, 2025). Because the DSHMRA was conceived as a provisional measure prior to the 1994 establishment of the ISA, its current application lacks historical and legal justification (TIME, 2025).

The ISA Secretary-General responded by affirming that no State may unilaterally exploit the Area outside UNCLOS (ISA, 2025b), a stance unusually united and supported by China, the European Union, and most member States (CSIS, 2025; Lowy Institute, 2025).

Doctrinally, the United States relies on its status as a persistent objector to Part XI of UNCLOS (Naval War College International Law Studies, 2025). However, this position has two structural weaknesses: first, three decades of de facto compliance and lack of unilateral operations undermine the behavioral consistency required by the persistent objector doctrine; second, the "common heritage of mankind" principle (UNCLOS Art. 136) may have acquired erga omnes customary status, making unilateral operations an internationally wrongful

act under general international law (Freestone, 2011; Lowy Institute, 2025). If the principle has attained the status of customary international law (a contested question) but one increasingly supported by generalised state practice and opinio juris reflected in near-unanimous support for the ISA, then unilateral United States operations in the CCZ would constitute not merely a conventional violation but an internationally wrongful act under general international law, opposable erga omnes by any member of the international community.

An effective conflict between U.S. operations and Chinese ISA contracts in the CCZ could trigger multiple scenarios:

- An Advisory Opinion from the Seabed Disputes Chamber on whether the common heritage principle binds non-Parties as custom.
- Bilateral Sino-American escalation in the CCZ, potentially acquiring a security dimension due to the dual-use capabilities of Chinese AUVs (CSIS, 2025).
- Multilateral pressure driven by the entry into force of the BBNJ Agreement (Article 7), prompting the U.S. to modulate its posture, echoing how international ocean governance successfully halted industries during the 1982 whaling moratorium (DLA Piper, 2025a).

3. **Technological Innovation, Impact Mitigation, and Monitoring Systems.**

3.1. *State of the Art in Extraction Technology.*

The technical system for polymetallic nodule extraction comprises three principal subsystems: the Deep-Sea Mining Vehicle (DSMV), the riser and lift system, and the surface support vessel. Among the technical paradigms historically tested, the pipeline-lift system has consolidated as the most efficient and is currently adopted by commercial actors (Zhang et al., 2024).

The DSMV combines a collection system for nodule capture with a locomotion system adapted to low-density, high-compressibility sediments (Zhang et al., 2024). The principal unresolved technical problems include vortex-induced vibrations (VIV) in the riser, solid accumulation in transport sections, and optimisation of the balance between drag water flow and nodule capture efficiency without excessive fine sediment resuspension. These limitations have direct regulatory implications: without mandatory minimum technical specifications on collector design and drag-flow management, the current RRP drafts cannot guarantee that contractors implement available best practices.

3.2. *Emerging Extraction Paradigms: Selective Robotics and Artificial Intelligence.*

The most significant recent technological advance in nodule collection is the development of vision-guided selective systems, which depart from conventional indiscriminate drag collectors. Impossible Metals has developed the Eureka autonomous underwater vehicle (AUV), designed to remain suspended

above the sediment and collect nodules selectively through computer vision and deep neural networks, while avoiding organisms detected on their surface (Impossible Metals, 2025; Deep-Sea Mining Watch, 2024).

The potential of artificial intelligence (AI) to reduce environmental impact is real but bounded. Computer vision may reduce sediment disturbance through more precise nodule capture, but it does not eliminate impacts on the benthic biotope or fine particle resuspension associated with vehicle propulsion (AZoMining, 2025). This is regulatorily relevant: approval of exploitation work plans based on Eureka-type technologies should require operational demonstration at commercial scale, not merely prototype results.

Deep learning applications in benthic biodiversity assessment can automate seabed image analysis and improve ecological baselines, although generalisation beyond the CCZ remains unresolved (Cuvelier et al., 2024). Real-time machine-learning monitoring can also detect anomalies and activate shutdown protocols when thresholds are reached (Science Array, 2025). However, without internationally agreed standards for such thresholds, this capability lacks regulatory content. The technology exists; the normative framework that makes it mandatory does not.

3.3. Plume Monitoring Systems: AUVs, Remotely Operated Vehicles, and Sensor Networks.

Monitoring sediment plumes generated by DSM is one of the greatest technical challenges in the environmental governance of this industry, due to their spatial dispersion and the extreme conditions of the deep-sea environment. The reference strategy integrates bottom-moored platforms, autonomous underwater vehicles (AUVs), and remotely operated vehicles (ROVs) in distributed sensor networks (Gillard et al., 2025; Sea Technology, 2024).

Independent trials monitored by the JPI-Oceans MiningImpact consortium and NORI's 2022 tests show that plume monitoring requires dense sensor deployments, mobile platforms, and real-time data collection. The 2021 trial revealed plume dispersion of up to 4.5 km from the impact site, while under strong current conditions plume transport may exceed 100 km, confirming that stationary networks alone are insufficient to capture the full extent of sediment dispersion (Gillard et al., 2025; Sea Technology, 2024).

This limitation has driven the development of mobile monitoring strategies based on AUV fleets, including systems capable of updating routes in real time and estimating plume boundaries dynamically (Von See et al., 2025; Zhang and Li, 2024). These advances are promising, but their integration into a mandatory independent monitoring regime requires technical and financial resources that current RRP drafts do not guarantee.

3.4. Surface Monitoring Technologies: Satellites, Buoys, and Acoustic Sensors.

Satellite remote sensing enables continuous, non-invasive observation of surface operations, including vessel tracking, detection of surface turbidity, and monitoring of oceanographic

conditions (Farmonaut, 2025; Zheng et al., 2021). Next-generation constellations have improved spatial resolution and revisit frequency, making near-continuous monitoring technically feasible. However, optical satellite sensitivity decreases rapidly below the first metres of the water column, limiting detection of deep intermediate-water plumes and leaving the subsurface impacts most relevant for governance largely invisible.

Oceanographic buoys equipped with sensors for temperature, salinity, current, turbidity, and fluorescence provide continuous water-column data. Integrated with satellite data and AUVs, they form a multi-platform monitoring architecture capable of feeding real-time databases via satellite communications, allowing the ISA and independent monitors to access environmental parameters during operations rather than relying only on contractors' post-operational reports (Sea Technology, 2024; Maarco Francis, 2025).

Broadband multibeam sonar mounted on AUVs remains one of the most effective tools for seabed mapping and assessment of nodule abundance and distribution. Acoustic Doppler Current Profiler (ADCP) sonar enables continuous current profiling in the water column, which is essential for predicting and tracking benthic plume dispersion (Gillard et al., 2025; Sea Technology, 2024).

3.5. Numerical Plume Dispersion Models and Digital Twins.

Numerical plume dispersion models are essential for predicting plume behavior beyond direct observation capacity. Oceanic digital twins (DTs) offer a promising tool for adaptive DSM management by enabling impact scenario modelling, simulation of perturbation effects, and continuous updating with real-time monitoring data (Jacobs et al., 2023). However, their application to DSM remains limited: without complete biodiversity baselines and validated ecological models, digital twins may reproduce sediment physics but cannot adequately capture ecological responses (Rosenbaum & Downes, n.d).

This limitation creates a risk of technologically legitimised self-monitoring. If real-time monitoring is operated and reported exclusively by contractors without independent verification, its regulatory value is null. The "traffic light" system developed by the MiningImpact project links suspended particle thresholds to operational responses: continuation, reduction of extraction intensity, or shutdown (Science Array, 2025). For this system to have regulatory value, thresholds must be fixed in the RRP and compliance verified by independent monitors, which current drafts do not unambiguously guarantee (Pickens et al., 2023; DSCC, 2025).

3.6. Sediment Re-Injection Technology and Its Limitations.

Deep re-injection of waste material is proposed as the main mitigation measure for the intermediate-water plume. However, it requires additional pipework, increases complexity and cost, and its environmental efficacy depends on injection depth and local currents (Sha et al., 2024). Moreover, even low concentrations of DSM sediment may exert mechanical and toxicological effects on cold-water corals, meaning that no injection depth fully eliminates risks to water-column organisms (Carreiro-Silva

et al., 2022). Current RRP drafts establish neither a minimum re-injection depth nor specific technical requirements for discharge systems, leaving key decisions to contractors and weakening enforceability of environmental standards.

3.7. Integrated Assessment: The Technology-Regulation Gap.

The preceding analysis reveals a consistent pattern: monitoring and mitigation technologies have advanced significantly, but their translation into concrete, independently verified regulatory commitments remains indeterminate. This is the most acute manifestation of regulatory lag in the DSM context.

None of the available or emerging mitigation technologies can eliminate DSM impacts at commercial scale. Three limitations must be distinguished. First, physical limits: once generated, the benthic plume cannot be recovered; Gillard et al. (2025) show re-sedimentation of 2–3 cm and dispersion up to 4.5 km, while deep re-injection cannot prevent local re-sedimentation. Second, ecological limits: long-term evidence from the DISCOL experiment shows that benthic communities have not recovered after three decades, while predictive models operate with radically incomplete baselines (Jones et al., 2025; Bell et al., 2025). Third, verification limits: without independent monitoring and binding standards, contractors' mitigation claims cannot be verified.

Technological investment is advancing faster than regulatory elaboration. This temporal asymmetry favors actors with greater investment capacity, allowing them to consolidate operational positions before stricter standards are adopted. The regulatory implication is direct: the precautionary principle requires proof of harmlessness before, not after, commercial operations.

4. Key actors, Authorisations, and the Nauru Case Study.

4.1. Principal Actors: Companies and Consortia.

The actor landscape reflects a combination of private and State strategic interests. TMC, with its subsidiaries NORI, TOML, and DeepGreen, is the primary driver behind the invocation of the two-year rule (Blanchard et al., 2023). Impossible Metals develops selective collection technology and operates under NOAA permits (Grist, 2025). Global Sea Mineral Resources (GSR) conducted trials of the Patania II collector in 2021 with independent scientific monitoring. Among state consortia, China holds five exploration contracts (more than any other country) and has signed agreements with Pacific island states (CSIS, 2025). Other key state operators include KIOST (Republic of Korea), Yuzhmorgeologiya (Russia), BGR (Germany), NIO and NIOT (India), and IFREMER (France) (Blanchard et al., 2023).

4.2. Case Study: Nauru and the Two-Year Rule.

Nauru's invocation of the two-year rule in June 2021 illustrates the tension between accelerated commercial development and cautious governance. Singh (2022) analyses three disputed legal questions: whether the obligation to "consider" implies provisional approval; what standards the Council must apply

in the absence of RRPs; and whether a provisional approval could be challenged. Willaert (2021) underscores that the provision was conceived as a last-resort mechanism, not as a tool for premature exploitation. From an environmental justice perspective, the contractual relationship between Nauru and TMC raises questions as to whether the decision reflected the long-term interests of the micro-State or responded to short-term corporate incentives (Macchi, 2025).

5. Multilevel Governance: Architecture, Actors, and Interactions.

5.1. The International Governance System: ISA Structure and Functioning.

The ISA's mandate combines regulatory functions, quasi-commercial management of the Area, and the guarantee of marine environmental protection (Blanchard et al., 2023). Structurally, it operates through four principal organs: The Assembly, the Council (36 elected members), the Legal and Technical Commission (LTC), and the Secretariat, as summarized in Table 1 (DLA Piper, 2025b). The Enterprise, the ISA's commercial operational arm, is not yet fully operational. The consensus requirement for substantive decisions adds a layer of complexity that explains the slow normative process (Singh, 2022; Pickens et al., 2023). Furthermore, debates regarding corporate access requests have raised concerns about potential "corporate capture" of the body (Earth Negotiations Bulletin, 2025; DSCC, 2025).

Table 1: ISA Organizational Structure and Functions in the Mining Code Context (2025).

Body	Composition	Principal Function	Status in Negotiations
Assembly	171 States + EU	General policy; RRP approval	Could not agree on General Environmental Policy; review deferred to ISA-31
Council	36 elected members	Executive organ; negotiates and adopts RRPs	Completed second reading of Art 1–107; text with brackets
LTC	Designated experts	Drafts regulations; supervises contracts	Identified 4 contractors with potential non-compliance
Secretariat	SG + staff	Administrative support; text preparation	New SG Carvalho (since January 2025); greater scientific emphasis
The Enterprise	No permanent staff	ISA's commercial arm	No effective operational capacity

Source: Authors.

5.2. The Mining Code in Detail: Structure, Outstanding Issues, and Cross-Cutting Questions.

The "Mining Code" is a composite instrument comprising three levels: binding RRPs; non-binding standards and guidelines; and management tools, such as Regional Environmental Management Plans (REMPs) (ISA, 2025a; Timelex, 2025). The consolidated text of 107 articles, which underwent a complete second reading during the 2025 Council sessions, is organised into ten parts covering general provisions, exploitation contracts, financial terms, marine environmental protection, inspection and enforcement, the ECF, the Enterprise, underwater cultural heritage, mine closure, and final provisions (ISA, 2025a).

A significant 2025 advance is the operationalization of the precautionary principle into quantitative, binding environmental thresholds for key mining pressures, including suspended particle concentrations, noise and light pollution, sediment plume toxicity, and greenhouse gas emissions (Timelex, 2025). However, the 2025 deliberations revealed persistent disagreement regarding measurement methodologies and the specific authority, whether the ISA, the contractor, or an independent third party, responsible for determining compliance when a threshold is exceeded, as summarized in Table 2.

Table 2: Principal Outstanding Regulatory Issues in the Mining Code Draft (ISA-30, 2025).

Thematic Area	Outstanding Issue	Nature of Disagreement	Implication
Financial terms	Royalty rates and distribution	Divergence between exporting and investing countries	High: economic viability and redistribution
Fiscal equalisation	Effective rate comparable to terrestrial mining	No consensus on methodology	Medium: competitive distortion
Environmental protection	Quantitative thresholds for acceptable harm	Disagreement on measurement methods	Very high: without thresholds no shutdown criterion exists
ICE mechanism	Composition and powers of Compliance Committee	Tension between independence and representation	High: without robust mechanism, compliance is voluntary
ECF	Sources of funding and amounts	Divergence on strict vs. fault-based liability	Very high: harm goes unremedied
Effective control	Test for State control over contractor	Risk of forum shopping	High: enables convenience sponsorship
Mine closure	Plans, guarantees, and post-closure liability	No agreement on monitoring duration	High: residual damage persists for decades

Source: Authors.

5.3. The ICE Mechanism: Design, Limitations, and International Comparison.

The design of a robust ICE (Inspection, Compliance and Enforcement) mechanism is the keystone of DSM governance. Springer's (2025) analysis of national compliance frameworks in principal Sponsoring States reveals disparities that are a source of systemic risk, as shown in Table 3. Monetary sanctions for non-compliance extend from minor fines (~USD 7,000 in Japan or USD 40,000 in Singapore) to substantial penalties (>USD 2 million in Belgium or USD 330,000 per day in Kiribati) (Lily & Chakraborty, 2025). This variability creates incentives for "forum shopping," replicating the classic flags of convenience problem.

Table 3: Comparative National Compliance Frameworks for DSM Sponsoring States (Selection).

Country	National Law	Maximum Penalty	Strict Liability	Independent Oversight
Belgium	Prospecting Act 2024	>USD 2M	Partial	Yes
Kiribati	Seabed Minerals Act	USD 330,000/day	No	No
Japan	Marine Mining Act	~USD 7,000	No	Partial
Singapore	Deep Sea Mining Act	~USD 40,000	No	No
Nauru	Deep Sea Mining Act 2015	Variable	No	No (self-regulation)
Norway	Seabed Minerals Act 2019	High	Yes	Yes (moratorium to 2029)
Germany	Meeresbodenbergbaugesetz	High	Yes	Yes
France	No specific legislation	N/A	N/A	N/A (moratorium)

Source: Authors.

6. The Multilevel Normative Framework: National, Regional, and International.

6.1. The National Dimension: Sponsoring and Coastal State Legislation.

Comparative practice reveals a highly heterogeneous landscape: while nations like Belgium and Germany have adopted strict environmental due diligence standards, others possess frameworks of limited technical stringency, fueling the risk of convenience sponsorship. In domestic waters, Norway approved the opening of 281,000 km² of its EEZ to commercial exploration in January 2024, but subsequent parliamentary pressure led to the suspension of its first licensing round until at least 2029 (DLA Piper, 2025a). Meanwhile, France and Germany maintain strong opposition to DSM in international waters, and the European Union still lacks a binding common position. Table 4 summarizes this typology of national positions on DSM.

Table 4: National Positions on DSM: Typology and Examples (December 2025).

Category	Position	Representative Countries	Basis
Favourable to rapid exploitation	Immediate advancement	USA, China, Cook Islands, Nauru, Tonga	Supply security; economic sovereignty
Regulated precaution	Only with complete Mining Code	Germany, India, Brazil, Japan, Korea	Industrial interests + environmental requirements
Precautionary pause	No exploitation until science and regulation mature	UK, New Zealand, Canada, Mexico	Precautionary principle; irreversibility
Moratorium/Prohibition	Indefinite or permanent prohibition	France, Portugal, Spain, Finland, Ireland	Unacceptable risk to abyssal ecosystems
No defined position	Strategic abstention	Multiple developing countries	Limitations of technical capacity

Source: Authors.

6.2. The BBNJ Agreement and Its Interaction with the ISA Regime.

The adoption of the BBNJ Agreement in June 2023 and its entry into force on 17 January 2026, following its 60th ratification in September 2025, represents the most significant development in the international law of the sea since UNCLOS, directly impacting DSM governance (Gibson Dunn, 2025). The agreement establishes a legally binding framework for conserving marine biodiversity in areas beyond national jurisdiction, geographically encompassing the Area. While it does not directly regulate mineral mining, its provisions on EIAs, area-based management tools (ABMTs), and marine protected areas create a normative context that inevitably interacts with the DSM regime (Vliz et al., 2025; Lily & Robb, 2025). Crucially, Article 7 explicitly reaffirms the common heritage of mankind principle, strengthening the legal prohibition on unilateral appropriation that underlies the challenge to the Trump Executive Order.

6.3. Regional Environmental Management Plans: Key Tool and Current Deficiencies.

REMPs are spatial management instruments establishing exclusion zones and prohibited reference zones. Although the

ISA adopted the first REMP for the CCZ, Du Preez et al. (2025) identify two critical structural deficiencies: the management framework assumes that mineral deposits are distributed in separate habitats, ignoring significant co-occurrence documented in the North Pacific, and the current CCZ REMP was conceived exclusively for abyssal plains, making it manifestly inadequate for managing areas where nodules occur on or adjacent to seamounts, ecosystems of considerably greater biodiversity and fragility (Du Preez et al., 2025).

7. Prospective Analysis: Governance Scenarios 2026-2030.

7.1. Scenario A: Mining Code Adopted with Robust Standards.

Inter-sessional negotiations resolve outstanding issues, and the ISA Council adopts a complete Mining Code in 2026, including binding environmental thresholds, an independent Compliance Committee, and real-time public monitoring. Commercial exploitation begins between 2028 and 2030 (Earth Negotiations Bulletin, 2025).

7.2. Scenario B: Regime Fragmentation and Regulatory Competition.

United States pressure to operate outside the ISA and the failure of Mining Code negotiations generate fragmentation. TMC obtains NOAA permits under the DSHMRA, China responds in its contract area, and other actors seek national permits under permissive laws, triggering dispute settlement before the Seabed Disputes Chamber (DLA Piper, 2025a; Lowy Institute, 2025).

7.3. Scenario C: De Facto Moratorium by Emerging Consensus (Intermediate).

Resistance to the Trump Executive Order, growing support for a precautionary pause, the strengthening of the BBNJ framework, and ESG pressure from downstream industries create a de facto consensus delaying exploitation until at least 2030 (Tanaka & Jaekel, 2025; DSCC, 2025). A sub-variant involving a weak Mining Code adopted with insufficient standards remains possible at approximately 20%

8. Conclusions and Policy Recommendations.

The analysis presented leads to three convergent conclusions:

At the normative level, the absence of an adopted Mining Code, combined with pressure from the two-year rule and the unilateral threat of the United States Executive Order, has generated unacceptable legal indeterminacy.

At the level of responsibility, deficiencies in due diligence mechanisms, the lack of contractor eligibility standards, and the indeterminacy of the ECF leave the question of liability for transboundary harm unresolved.

At the technological level, available systems are insufficient to prevent large-scale impacts in the absence of mandatory standards with independent verification.

The central conclusion is that the current DSM governance trajectory is structurally incapable of ensuring environmental protection under commercial pressure. Under the precautionary principle enshrined in UNCLOS Article 145, a governance regime that cannot guarantee environmental protection does not satisfy the normative threshold required to authorize commercial exploitation.

Policy Recommendations

Formally declare a precautionary pause: The ISA Council should adopt a binding decision prohibiting the approval of any exploitation work plan until a complete Mining Code is adopted, grounded in UNCLOS Article 145 and the 2011 Advisory Opinion.

Establish Best Available Technology (BAT) standards: The RRP must incorporate BAT standards with precise technical definitions, and the "traffic light" ecological threshold system must be defined via quantifiable, binding criteria.

Mandate independent monitoring: The RRP must require multi-platform monitoring networks operated by independent third parties, with data accessible in real time.

Strengthen State responsibility and eliminate liability caps: Sponsoring States must adopt national legislation incorporating strict liability for environmental harm caused by their contractors, without pre-established quantitative limitations, and implement strict contractor eligibility criteria.

Redesign the ECF with mandatory insurance: The ECF must be funded through mandatory environmental insurance premiums proportional to projected extraction volumes, managed by an independent body with scientific and civil society representation (Wang et al., 2025).

Extend management frameworks to seamounts: REMPs must be urgently revised to encompass ecosystems associated with seamounts, suspending exploitation where nodule - seamount co-occurrence has not been characterised (Du Preez et al., 2025).

Articulate a firm multilateral response and request an ITLOS Advisory Opinion: The ISA and its member States must articulate a coherent legal response to unilateral operations, including requesting an ITLOS Advisory Opinion to clarify whether the common heritage of mankind principle binds non - Parties as custom.

Acknowledgment

The authors declare no funding sources or conflicts of interest in relation to this research.

References

- AZoMining. (2025, April 17). Can AI help reduce the environmental impact of deep-sea mining? AZoMining. <https://www.azomining.com/Article.aspx?ArticleID=1857>.
- Bell, K. L. C., Kennedy, B. R. C., Leitner, A. B., Rountree, R. A., Singh, H., & Juanes, F. (2025). How little we've seen: a visual coverage estimate of the deep seafloor. *Science Advances*, 11(19). <https://www.science.org/doi/10.1126/sciadv.adp8602>.

- Blanchard, C., Harrould-Kolieb, E., Jones, E., & Taylor, M. L. (2023). The current status of deep-sea mining governance at the International Seabed Authority. *Marine Policy*, 147, 105396. <https://doi.org/10.1016/j.marpol.2022.105396>.
- Carreiro-Silva, M., Martins, I., Riou, V., Raimundo, J., Caetano, M., Bettencourt, R., et al. (2022). Mechanical and toxicological effects of deep-sea mining sediment plumes on a habitat-forming cold-water octocoral. *Frontiers in Marine Science*, 9, 915650. <https://doi.org/10.3389/fmars.2022.915650>.
- Center for Strategic and International Studies (CSIS). (2025, May 1). Trump's deep-sea mining executive order: The race for critical minerals enters uncharted waters. <https://www.csis.org/analysis/trumps-deep-sea-mining-executive-order-race-critical-minerals-enters-uncharted-waters>.
- Cuvelier, D., Zurowietz, M., & Nattkemper, T. W. (2024). Deep learning-assisted biodiversity assessment in deep-sea benthic megafauna communities. *Frontiers in Marine Science*, 11, 1366078. <https://doi.org/10.3389/fmars.2024.1366078>.
- Deep-Sea Conservation Coalition (DSCC). (2025, June). Policy recommendations on deep-sea mining - Part II of the 30th session of the International Seabed Authority. <https://deep-sea-conservation.org/>.
- DLA Piper. (2025a, July 11). Deep sea mining uncovered: To pause or proceed? Part Three. <https://www.dlapiper.com/>.
- DLA Piper. (2025b). Deep sea mining uncovered: From exploration to exploitation. Part Two. <https://www.dlapiper.com/>.
- Du Preez, C., Gartner, H., Murdock, S., & Tunnicliffe, V. (2025). Beyond the plains: deep-sea mining of polymetallic nodules on and around seamounts. *Frontiers in Marine Science*, 12, 1666150. <https://doi.org/10.3389/fmars.2025.1666150>.
- Earth Negotiations Bulletin (IISD). (2025, July). Summary report, 7–25 July 2025: International Seabed Authority, 30th Annual Session, Part II. <https://enb.iisd.org/>.
- Farmonaut. (2025). Deep sea mining 2025: Powerful tech shaping ocean resources. <https://farmonaut.com/>.
- Foley Hoag LLP. (2025, May 29). A challenge to the constitution for the ocean? Understanding Trump's deep sea mining executive order. <https://foleyhoag.com/>.
- Freestone, D. (2011). Advisory opinion of the Seabed Disputes Chamber of the ITLOS on responsibilities and obligations of States sponsoring persons and entities. *ASIL Insights*, 15(7). <https://asil.org/insights/volume-15-issue-7/>.
- Gibson Dunn. (2025, November 18). Global treaty on marine biodiversity beyond national jurisdiction to enter into force in January 2026. <https://www.gibsondunn.com/>.
- Gillard, B., Purkiani, K., Chatzievangelou, D., Vink, A., Iversen, M. H., & Thomsen, L. (2025). Monitoring benthic plumes, sediment redeposition and seafloor imprints caused by deep-sea polymetallic nodule mining. *Nature Communications*, 16, Article 835. <https://doi.org/10.1038/s41467-025-56311-0>.
- Greenpeace USA. (2025, April 24). US government confirms their support for deep sea mining plans that bypass United Nations. <https://www.greenpeace.org/usa/>.
- Grist. (2025, December 22). What changed for deep-sea mining in 2025? Everything. <https://grist.org/>.
- Harvard Environmental & Energy Law Program (EELP). (2025). Deep sea mining regulatory tracker. <https://eelp.law.harvard.edu/tracker/deep-sea-mining/>.
- Impossible Metals. (2025). Eureka autonomous underwater vehicle. <https://impossiblemetals.com/>.
- Inside Climate News. (2025, May 18). Trump promotes deep-sea mining bypassing international law. <https://insideclimatenews.org/>.
- International Seabed Authority (ISA). (2025a). Revised consolidated text of the draft exploitation regulations. ISBA/30/C/5. <https://www.isa.org.jm/>.
- International Seabed Authority (ISA). (2025b, April 25). Statement on the US Executive Order. <https://isa.org.jm/>.
- International Tribunal for the Law of the Sea (ITLOS), Seabed Disputes Chamber. (2011). Responsibilities and obligations of States sponsoring persons and entities (Advisory Opinion No. 17). ITLOS/PV.11/1. <https://www.itlos.org/en/main/cases/list-of-cases/case-no-17/>.
- Jacobs, K., O'Dowd, C. D., & Wouters, B. (2023). Digital twins: a stepping stone to achieve ocean sustainability? *npj Ocean Sustainability*, 2, Article 27. <https://doi.org/10.1038/s44-183-023-00023-9>.
- Jones, D. O. B., et al. (2025). Long-term impact and biological recovery in a deep-sea mining track. *Nature*, 631, 60–65. <https://doi.org/10.1038/s41586-024-07596-4>.
- K&L Gates. (2024, June 10). Deep sea mining — What is happening with deep-sea mining? <https://www.klgates.com/>.
- Lily, H., Chakraborty, A. (2025). Navigating Challenges in Inspection, Compliance and Enforcement ('ICE') for Deep-Seabed Mining Beyond National Jurisdiction. In: Sharma, R. (eds) *Deep-Sea Mining Management, Policy and Regulation*. Springer, Cham. https://doi.org/10.1007/978-3-031-92737-9_15.
- Lily, H., & Robb, S. (2025, December 4). Two birds, one bill: how BBNJ national legislation can tackle UNCLOS deep seabed mining gaps. *EJIL: Talk!*. <https://www.ejiltalk.org/two-birds-one-bill-how-bbnj-national-legislation-can-tackle-unclos-deep-seabed-mining-gaps/>.
- Lowy Institute. (2025, October 24). Critical minerals: The US bid to bypass international rules on deep sea mining. <https://www.lowyinstitute.org/>.
- Macchi, C. (2025). Corporate responsibility and deep seabed mining: the limits of due diligence. *Business and Human Rights Journal*, 10(1), 122–146. <https://doi.org/10.1017/bhj.20-24.27>.
- Martin, C., Weilgart, L., Amon, D. J., & Müller, J. (2021). Deep-sea mining: a noisy affair. *OceanCare*. https://www.oceancare.org/wp-content/uploads/2021/12/Deep-Sea-Mining_A-noisy-affair_Report-OceanCare_2021.pdf.
- Mondaq. (2026, January 28). Deep-sea mining: navigating legal challenges. <https://www.mondaq.com/>.
- Naval War College International Law Studies. (2025). The U.S. executive order on seabed mining is consistent with international law. *International Law Studies*, 106. <https://digitalcommons.usnwc.edu/cgi/viewcontent.cgi?article=3113&context=ils>.
- Pickens, C., Lily, H., Harrould-Kolieb, E., Blanchard, C., & Chakraborty, A. (2023). From what-if to what-now: status of

the deep-sea mining regulations and underlying drivers for outstanding issues. *Marine Policy*. <https://doi.org/10.1016/j.marpol.2023.105967>.

Rosenbaum, H., & Downes, L. (n.d.). Digital twin technology and adaptive management systems for deep sea mining Limitations and the Risk of Self-Regulation. <https://dsm-campaign.org/digital-twin-tech-in-deep-sea-mining/>.

Science Array. (2025, September 22). Deep sea tech 2025: AI robots reveal ocean's hidden world. <https://nature.sciencetrack.com/>.

Sea Technology Magazine. (2024, December 20). AUVs for environmental oversight of deep-sea mining. <https://sea-technology.com/>.

Seas at Risk. (2025, July 25). Global deep-sea mining talks yield mixed verdict. <https://seas-at-risk.org/>.

Sha, F., Xi, M., Wen, Z., Chen, X., Zuo, Y., Xu, J., Zhang, M., & Niu, H. (2024). A review on plumes generation and evolution mechanism during deep-sea polymetallic nodules mining. *Ocean Engineering*, 298, 117188. <https://doi.org/10.1016/j.oceaneng.2024.117188>.

Singh, P. A. (2022). The invocation of the "two-year rule" at the ISA: legal consequences and implications. *International Journal of Marine and Coastal Law*, 37(2), 375–412. <https://doi.org/10.1163/15718085-BJA10098>.

Stokstad, E. (2023). As prospect of unregulated deep-sea mining looms, scientists sound the alarm. *Science*, 381(6655), 263. <https://doi.org/10.1126/science.adj8304>.

Tanaka, Y., & Jaeckel, A. (2025). A pause or moratorium for deep seabed mining in the Area? *Ocean Development & International Law*, 56(1), 18–44. <https://doi.org/10.1080/00908320.2024.2439877>.

Theil, K., & Rahbar, M. (2024). Seabed mining and the accountability gap. *Leigh Day News Blog*. <https://www.leighday.co.uk/news/blog/2024-blogs/seabed-mining-and-the-accountability-gap/>.

TIME Magazine. (2025, June 17). Trump may be repeating Reagan's deep sea mining mistake. <https://time.com/>.

Timelex. (2025, December). Deep-sea mining beyond national jurisdiction: a legal and policy update. <https://www.timelex.eu/>.

United Nations. (1982). United Nations Convention on the Law of the Sea (UNCLOS). UN Treaty Series, vol. 1833. <https://treaties.un.org/doc/publication/unts/volume%201833/volume-1833-a-31363-english.pdf>.

University of Hawaii at Manoa. (2025). Deep-sea mining waste threatens life in the ocean's twilight zone. *Phys.org*. <https://phys.org/news/2025-11-kind-deep-sea-threatens-life.html>.

Vinson & Elkins. (2024, December). Update on Part II of the 29th session of the ISA negotiations. <https://www.velaw.com/>.

Vliz, N., Singh, P. A., & Jaeckel, A. (2025). The interaction between the BBNJ Agreement and the international deep sea mining regime. *Ocean Development & International Law*, 56(2), 176–213. <https://doi.org/10.1080/00908320.2025.2472-634>.

Von See, T. B., Greinert, J., & Meurer, T. (2025). Multi-AUV sediment plume estimation using Bayesian optimization. *Frontiers in Marine Science*, 11, 1504099. <https://doi.org/10.3389/fmars.2024.1504099>.

Wang, Y., Wang, Y., & Pan, X. (2025). Optimization of the environmental compensation fund system for the area. *Frontiers in Marine Science*, 12, 1638999. <https://doi.org/10.3389/fmars.2025.1638999>.

Willaert, K. (2021). Under pressure: the impact of invoking the two-year rule within the context of deep sea mining. *International Journal of Marine and Coastal Law*, 36(3), 505–513. <https://doi.org/10.1163/15718085-bja10068>.

Zhang, X., Zuo, Y., Wei, J., Sha, F., Yuan, Z., Liu, X., Xi, M., & Xu, J. (2024). A review on underwater collection and transportation equipment of polymetallic nodules. *Journal of Marine Science and Engineering*, 12(5), 788. <https://doi.org/10.3390/jmse12050788>.

Zhang, Y., & Li, S. (2024). Dynamic boundary estimation of suspended sediment plume by AUV sensing. *Sensors*, 24(24), 8182. <https://doi.org/10.3390/s24248182>.

Li, X., Liu, B., Zheng, G., Ren, Y., Zhang, S., Liu, Y., Gao, L., Liu, Y., Zhang, B., & Wang, F. (2020). Deep-learning-based information mining from ocean remote-sensing imagery. *National science review*, 7(10), 1584–1605. <https://doi.org/10.1093/nsr/nwaa047>.