Earth System Governance 24 (2025) 100249

Contents lists available at ScienceDirect

Earth System Governance

journal homepage: www.sciencedirect.com/journal/earth-system-governance

Exploring plausible future scenarios of deep seabed mining in international waters

Aurora Cato *, Philippe Evoy

IVM, Vrije Universiteit Amsterdam, Faculty of Science, NU building, 8th Floor, Wing A, De Boelelaan 1111, 1081 HV, Amsterdam, the Netherlands

A B S T R A C T

The global transition to renewable energy has intensified the demand for critical minerals, which are essential components in key green technologies. Many of these minerals are abundant on the international seabed, but negotiations surrounding deep-sea mining regulations have met significant challenges. Developing countries, having historically been marginalized in the benefits of resource extraction, have expressed concern about the regulatory framework for deep-sea areas. Additionally, scientific understanding of the potential ecological impacts of deep-sea mining on marine ecosystems remains limited. Despite these concerns, the economic incentives for exploiting deep-sea minerals are driving pressure to finalize regulatory frameworks and commence mining activities. While speculation abounds regarding the future trajectory of deep seabed mining, significant uncertainties persist when considering its development in international waters. This paper explores these uncertainties and examines the potential future implications of global policy decisions for both ecological sustainability and economic outcomes. Drawing on document analysis and expert interviews, we identify critical uncertainties and other drivers of change shaping the future of deep-sea mining. Using the 2 x 2 'intuitive logics' matrix method, we develop scenario narratives based on the two most critical uncertainties: the place of environmental management and redistribution of benefits in the nascent industry. The scenarios present possible futures for deep-sea mining in international waters, providing insights to inform regulatory decision-making.

1. Introduction

Climate change is a looming threat as it negatively impacts global food and water security, vital ecosystems, human health, and more. Human activities have unequivocally contributed to this issue through greenhouse gas emissions resulting primarily from the use of fossil fuels (IPCC et al., 2023). As awareness surrounding climate change increases, states have bolstered efforts to transition to renewable energy sources. Technological advancements needed to transition require critical minerals such as copper, lithium, nickel, cobalt, and rare-earth metals, which are sourced predominantly from China, the Democratic Republic of the Congo, and Chile (IEA, n.d.). These industries, however, are known to threaten vulnerable populations and degrade the terrestrial environment. Economic opportunities associated with renewable energy minerals, coupled with concerns about the long-term reliability of land-based sources, has reignited interest in deep seabed mining (DSM) (Levin et al., 2020). As pressure to harvest deep-sea resources increases, many unknowns still surround this future venture, which could generate global consequences if not anticipated carefully.

Deep seabeds, located more than 200 m below sea-level, contain several of the abovementioned critical minerals in cobalt-rich crusts, ferromanganese (polymetallic) nodules, and seafloor massive sulfides in habitats such as abyssal plains, hydrothermal vents, and seamounts along mid-ocean ridges (Cuyvers et al., 2018; Miller et al., 2018). One location in the central Pacific Ocean, the Clarion-Clipperton Zone (CCZ), contains up to five times the amount of critical minerals as land-based reserves, which, if extracted, could electrify one billion cars using 30% of the greenhouse gases associated with land-based mines (Levin et al., 2020). However, locations like the CCZ exist in international waters, presenting governance challenges. The prospect of DSM may be significant for both the renewable energy transition and to further economic development in the Global South, as the United Nations Convention on the Law of the Sea (UNCLOS) stipulates that activities on the international seabed "shall […] be carried out for the benefit of mankind as a whole" (Art. 140.1). As we further detail below, this implies a redistribution of the benefits derived from DSM. Nevertheless, extracting deep-sea minerals requires machinery that may harm unique ecosystems. The remoteness of deep-sea habitats has left them relatively unexplored, but studies indicate they harbor high biodiversity and provide important ecosystem services such as regulating global climate (Glover and Smith, 2003; IPBES, 2019). Highlighting how little is known about the seabed, one recent study found that polymetallic nodules can

* Corresponding author. IVM, Vrije Universiteit Amsterdam, Faculty of Science, NU building, 8th Floor, Wing A, De Boelelaan 1111, 1081 HV, Amsterdam, the Netherlands.

E-mail address: auroramcato@gmail.com (A. Cato).

https://doi.org/10.1016/j.esg.2025.100249

Received 9 October 2024; Received in revised form 22 January 2025; Accepted 21 February 2025

Available online 13 March 2025

produce oxygen, supporting deep-sea ecosystems in a way previously unknown to science (Sweetman et al., 2024). The vitality of the ocean for Earth functions is thus vulnerable to unstudied impacts of DSM (Wang et al., 2023). These saliencies highlight the need for clear governance structures and policy choices that effectively meet society's demands while protecting vital ecosystems.

This paper begins by providing background on the DSM regime, reflecting on DSM's current challenges, and establishing where this study contributes to the field. Subsequently, it describes a theoretical framework and methodology for the formulation of alternative future scenarios, which can allow decision-makers to visualize the potential impacts of different regulatory choices. Lastly, the paper presents the results of the scenario analysis, discusses its implications for the future, and outlines policy recommendations.

2. The challenges of governing DSM

2.1. Background

Interest in DSM began when J. L. Mero published *Mineral Resources of the Sea* in 1965, which characterized the deep sea as a limitless source of critical minerals. While Mero's (1965) estimates proved erroneous, they spurred discussions about exploiting ocean minerals (Nandan and Lodge, 2002). Furthermore, Meadows et al. forecasted global mineral shortages in *The Limits to Growth* (1972) (Glasby, 2002). This, coupled with concerns over the reliability of land-based mineral supplies, initiated a first wave of DSM research (Ranganathan, 2014).

As knowledge grew and economic possibilities became more tangible, countries began to negotiate the legal structure for deep seabeds in international waters. These negotiations concluded with the adoption of the 1982 United Nations Convention on the Law of the Sea, which designated deep seabeds beyond national jurisdiction as 'the Area'. UNCLOS assigned regulatory powers to a centralized body, the International Seabed Authority (ISA), to govern the Area as the common heritage of humankind. However, the ISA only became effective in 1994, as the path to its implementation was hindered by disputes over benefit-sharing between the Global North and Global South. The dispute eventually waned with economic liberalization in the 1990s and lost political relevance as nations abandoned the idea of DSM as a promising commercial venture (Ranganathan, 2014).

A resurgence of interest arose years later with demands for green technology and perceived shortages of land-based minerals (Glasby, 2000; Sparenberg, 2019). Accompanying this period was a shift in focus from solely equitable benefit distribution toward environmental protection (Kung et al., 2021). After research resumed in the 2000s, the ISA developed regulations for its Mining Code on the exploration of minerals in the Area. Thus far, the ISA has granted 15-year exploration contracts in the CCZ, Indian Ocean, Mid-Atlantic Ridge, and Pacific Ocean to 21 companies and sponsoring states including China, the United Kingdom, Belgium, Germany, France, and Japan (ISA, 2022b). Since 2011, the ISA has worked to develop exploitation regulations and allow mining to commence. As energy demands increase, actors have recognized the associated economic opportunities and have pressured the ISA to finalize its Mining Code. Specifically, the island state of Nauru triggered the 'two-year rule' in 2021, a provision of UNCLOS that requires the ISA to complete exploitation rules within two years of the request. Although the ISA has a working draft of exploitation regulations (ISA, 2019), it failed to finalize them by 2023 and seeks their adoption in 2025 (Pickens et al., 2024). The ISA's Draft Strategic Action Plan for 2024–2028 includes directions toward protecting the environment, equitable benefit sharing, promoting transparency and participation within the ISA, and enforcing its regulations. However, the achievement of these goals is surrounded by uncertainty. Ambiguity and disagreements within the ISA compromise the possibility of reaching these targets and highlight the need to engage in prospective thinking about DSM.

Part XI of UNCLOS established the ISA to ensure the Area be governed as the 'common heritage of humankind' (CHM). This phrase was introduced in 1967 by Arvid Pardo, the Maltese representative to the UN General Assembly as a new status of the deep seabed (Vogler, 2012). The CHM concept establishes that deep seabed activities should favor humankind as a whole, specifically through benefits for developing states and marine environmental protection for future generations (Ranganathan, 2014). Upholding CHM requires non-appropriation/non-alienation, equitable benefit sharing, and the no harm principle for the Area. Therefore, no state can claim sovereignty over the Area, developing nations must have equal participation and access to its benefits, it must be used exclusively for peaceful purposes, and it must be protected ecologically. This presents a challenge for DSM governance since it requires balancing consideration for future generations, the marine environment, and an array of both economic and non-economic interests.

2.2. Current challenges

The lack of complete regulations and state eagerness to mine has led to ongoing research on governance problems and risks of ecological harm associated with DSM. Many contributions focus on issues at the ISA. Jaeckel et al. (2023) describe how the social legitimacy of DSM is compromised, based on questions about whether the ISA's decision-making processes truly act on behalf of humankind and whether they involve relevant actors to the extent necessary. Conde et al. (2022), Morgera and Lily (2022), and Willaert (2020) identify critical limitations in participation and stakeholder engagement within the ISA's decision-making, especially considering the CHM mandate. The transparency of ISA processes is questioned by Ardron et al. (2018) and Thompson et al. (2018), who highlight limited public access to ISA information. A long-running point of contention concerns an alleged lack of neutrality of the ISA Secretariat, often accused of favoring the interests of the mining industry, to the detriment of environmental regulations and the operationalization of the CHM principle (IISD, 2024b). Another key issue presented by Kim (2017), Pickens et al. (2024), and Wilde et al. (2023) is one of benefit distribution: will DSM save benefits for future generations, and will ISA redistribution mechanisms suffice for developing states? The numerous member states, all with diverging political and economic interests, contribute to the ISA's complex structure and thus constitute one of the main barriers to efficient decision-making about how to govern the Area appropriately.

Other authors such as Miller et al. (2018) and studies including MIDAS (2016) highlight the vulnerabilities of deep-sea ecosystems, environmental risks of DSM, and knowledge gaps about impacts. The implications of biodiversity loss are apparent, especially because marine biodiversity correlates with greater ecosystem services (Worm et al., 2006). However, there is a lack of data on deep-sea biodiversity and species connectivity, which imposes consequences of unknown scale on vital ecosystem functions (MIDAS, 2016). Thompson et al. (2018) and Levin et al. (2016) note how deep-sea organisms are characterized by slow growth rates, late reproduction, and low fecundity, rendering them vulnerable to human activities. Newer studies on abyssal plains and hydrothermal vents indicate connections between these ecosystems and wider global processes, though uncertainties remain on how mining disturbances will impact ecosystems long-term (Levin et al., 2020). Niner et al. (2018) conclude DSM will cause inevitable biodiversity loss, and therefore must be approached in an adaptive manner while further ecological knowledge develops. Adaptive management entails interventions based on increased understandings of biodiverse and complex systems, including careful monitoring of studied impacts and continual refinement of management and compliance practices (Jaeckel, 2016). To date, the ISA has not sufficiently integrated such management mechanisms (Jaeckel, 2016).

Ecological concerns, combined with governance challenges, exacerbate the need to consider different future scenarios of how DSM may develop. With remaining knowledge gaps about deep-sea ecosystems

and mining impacts, it is important that the ISA's regulations sufficiently uphold UNCLOS' mandate to protect the environment. Simultaneously, the ISA must adhere to the CHM principle by equitably allocating costs and benefits associated with exploitation. However, the noted lack of transparency, accountability, and complete regulatory structure within the ISA signifies the possibility of failure at fulfilling these objectives. Scenarios can help identify potential implications of different regulatory choices and inform decision-makers on the best paths forward. This paper fills the gap in existing DSM literature with such scenarios. More specifically, it aims to identify the most impactful and uncertain driving forces guiding the future of DSM in international waters, and to evaluate how different global policy choices could impact its development.

3. Methodology

3.1. Theoretical framework

This paper aims to sketch possible future trajectories of DSM and its governance, for the benefit of scholars and stakeholders. We root our analysis in futures studies, an academic field that acknowledges the future's unknowability while using it for present decision-making and strategic planning (Poli, 2017). As such, it provides an apt theoretical framework to apprehend the future of DSM. Futures studies often uses the 'scenario' concept, which, in simple terms, depicts a future state or development (Börjeson et al., 2006). Scenarios explore plausible, alternative futures based on various uncertainties, rather than solely forecasting the most likely outcome (Mahmoud et al., 2009; Wilkinson et al., 2013).

Scenario analysis is widely used in organizations that operate in volatile and unpredictable settings – such as businesses, militaries, and governments – as a powerful tool to enhance resilience and adaptability. By anticipating various potential developments, organizations minimize surprises and are quicker to react to changing circumstances. A frequently cited example of a successful application of scenario analysis is Royal Dutch/Shell's creation of an internal "Group Planning" department in the early 1970s, which anticipated a possible oil price surge due to geopolitical tensions. The department's report, produced just months before the 1973 oil crisis, allowed executives to prepare for this possibility, giving the company an enormous advantage over its competitors (Mietzner and Reger, 2005). As Cairns and Wright (2018) highlight, while scenarios can help identify potential risks, they also allow for early recognition of opportunities. As such, governments increasingly use foresight exercises in contexts where policies can positively impact future developments. For instance, the Dutch government has integrated scenario analysis into diverse policy areas, such as urban planning and energy production and consumption (Enserink et al., 2022). At the intergovernmental level, foresight research has become standard practice in organizations such as NATO or the European Union (Sus and Hadeed, 2020). Scenarios also have a long history in policy areas linked to resource exploitation and the environment, as exemplified by their use in the influential and aforementioned *The Limits to Growth* report (Meadows et al., 1972).

Scenario development can be quantitative, using modeling, or qualitative, using narratives. Quantitative scenario analysis relies on mathematical algorithms and relationships to represent well-understood, short-term systems. However, this method becomes limited for complex and long-term systems like the DSM regime, which involves multiple levels of decision-making and intricate biophysical processes. Qualitative scenarios help overcome these limitations by capturing factors like values, cultures, and institutions, that may lead to system shifts and surprises (Swart et al., 2004). They provide a complementary perspective to more formal modelling as they can challenge the assumptions that underly these models (Vervoort et al., 2014). As the novelty of DSM is associated with limited data availability and a wide range of non-quantifiable variables, this article employs qualitative narratives.

Scenario analysis is inherently interdisciplinary, which makes it an effective tool for synthesizing vast amounts of information associated with various fields that often work in silos. Socio-ecological scenarios built in this fashion enable policymakers to grasp the "big picture" of the issues at stake (Alcamo, 2008). The added value of our approach lies not in identifying drivers of change that experts in various disciplines have already recognized, but in anticipating their potential joint effects through a rigorous, structured method. In global policymaking, particularly in the case of DSM, where a wide range of diverse and often polarized actors are involved, scenario analysis can be highly valuable. Negotiators sometimes develop "tunnel vision," becoming overly focused on promoting their own priorities. By exploring multiple possible scenarios, decision-makers are encouraged to step outside of this narrow focus, helping them avoid groupthink and better preparing them for a variety of potential futures (Cairns and Wright, 2018).

3.2. Research method

This paper draws upon the 'intuitive logics' school of scenario building. 'Intuitive logics' emphasizes engaging intuition, challenging assumptions, and creating interpretations of the future for effective strategic and motivating purposes (Schwartz, 1996; van der Heijden, 2005). Through this approach, scenarios are presented as stories rather than as forecasting tools (Wilkinson et al., 2013). Schwartz (1996) highlights the need for organizations to develop plausible scenarios using intuitive logics, specifically by identifying critical uncertainties and driving forces, to anticipate changes and inform decision-making. Plausibility-based scenarios developed with intuitive logics are well-suited for complex environments such as the Area, since such systems are characterized by non-deterministic and uncertain behavior, as well as feedback loops (Mahmoud et al., 2009; Oteros-Rozas et al., 2015; Wilkinson et al., 2013). Van der Heijden (2005) expands on intuitive logics by emphasizing stakeholder engagement in scenario development to promote collaboration, help identify critical uncertainties, and gain diverse perspectives for better adaptable planning. Stakeholder inclusion is an integral part of scenario building for ecological systems as it produces new knowledge, supports creativity, mitigates the effect of academic experts' biases, and increases legitimacy in policy outcomes. As we further detail below, we thus interviewed important actors of DSM to validate our initial findings.

This paper employs an inductive method of scenario development, namely the 2 x 2 'scenario matrix' method. This method is based on quantitatively and/or qualitatively deriving the most impactful and uncertain drivers of change, hereafter referred to as 'critical uncertainties', that influence the future of a phenomenon over a medium- to long-term time horizon (Ramirez and Wilkinson, 2014). To identify these critical uncertainties, we classified drivers of change into three categories, varying in levels of impact and uncertainty, onto an "impact-uncertainty grid" (Dean, 2019). 'Critical uncertainties' have a high impact and high uncertainty, whereas 'key trends' are characterized by high impact but lower uncertainty. Other, less impactful drivers called 'secondary elements', which vary in terms of uncertainty, may still be relevant to scenario development. We then identified two drivers with the highest impact and uncertainty and developed them into axes for a 2 x 2 matrix, which depicts four distinct scenarios based on polarized extremes of these two critical uncertainties. We established each scenario around a set of descriptors, which we developed into a narrative. Descriptors are key dimensions, such as governance characteristics and industry structure, that shape the outcomes within each scenario (Yap et al., 2023). Lastly, we centered the scenario narratives around the drivers of change and the descriptors.

3.3. Data collection & analysis

We identified drivers of change and scenario descriptors primarily through a document analysis, which was corroborated by input from

expert and stakeholder interviews. The documents included academic literature on DSM ecology and governance, as well as news, blog, and website articles, international treaties, and documents produced by governments, NGOs, and international organizations. The analysis relied mostly on academic literature as scenario development requires significant expert input. Table 1 identifies the distribution of documents used for the analysis, and Appendix C depicts the comprehensive document list.

We used the program ATLAS.ti to code for the drivers of change and scenario descriptors. For each document, we coded the drivers of change mentioned as 'critical uncertainty', 'key trend', or 'secondary element', depending on how much the document emphasized each driver. We then generated a code co-occurrence analysis to reveal how often each driver was specified to influence DSM, and strategically placed them onto an impact-uncertainty grid. We determined drivers impactful if they appeared frequently within DSM discourses and uncertain if these discourses were often conflicting. We used the two drivers ranking highest on the grid as axes for a 2 x 2 matrix.

We developed each scenario primarily based on information from the document analysis. We coded each document for references to inductively derived descriptors such as 'industry structure' or 'strategies of private actors' to identify and organize information on each scenario's characteristics. This data guided how we wrote narratives using critical thinking and creativity to describe distinct and plausible futures for DSM based on variations within the descriptors. Despite the analysis having revealed some factors capable of halting DSM, we developed each scenario assuming it does go forward, as the objective of this paper is to inform global policy under such conditions.

To corroborate the document analysis, we conducted semi-structured interviews with important stakeholders and recognized experts, identified through the document analysis and snowball sampling. We asked the interviewees to identify drivers of change influencing DSM in the Area and used this input to adjust the main critical uncertainties. Interview questions also focused on how each expert characterized the future of DSM, to provide information for each scenario narrative. We transcribed and coded each interview in ATLAS.ti, using the above-mentioned 'drivers of change' and descriptors codes.

4. Results

4.1. Drivers of change

This section discusses how drivers of change were identified, classified within an impact-uncertainty grid and deemed relevant for plausible DSM scenarios. Fig. 1 depicts the coding frequency of each driver within the document analysis and interviews. The impact-uncertainty grid (Fig. 2) identifies the key trends, critical uncertainties, and secondary elements that contribute to the future of DSM. The grid was adjusted slightly after the interviews, as expert input is crucial for scenario development based on the most recent information.

The document analysis identified 'desire for economic growth, 'geopolitical concerns', 'mineral supply', and 'mining technology' as the key trends driving future DSM, as these were frequently associated with high importance and certainty. 'Desire for economic growth' reflects incentives for companies to capitalize on a novel resource base and motivations for states' to develop economically. Specifically, one interviewee acknowledged that once regulations are established, mining will occur "because you can make money out of it" (Interview 6, 2024). 'Geopolitical concerns' relates to Western worries about how "China's got a stranglehold on either mining or processing" minerals (Interview 3, 2024). Because of China's control of these supply chains (IEA, n.d., 2023; Tilot et al., 2021), many countries seek to mine the deep seabed to secure independent access to these resources (Interview 4, 2024). 'Mineral supply' encapsulates perceptions of diminishing supplies on land and that key minerals in the deep seabed, such as cobalt and nickel, are abundant (Interview 1, 2024; Kung et al., 2021; Li et al., 2021). Lastly, the analysis and interviews speculated future improvements in 'mining technology', although concurred less about current technological feasibility. Not only does technology appear to advance exponentially with time (Kurzweil, 2004), but interviewees also predicted that technologies will improve and become less environmentally damaging (Interview 2, 2024; Interview 3, 2024). These key trends are pivotal as they will likely impact DSM regardless of other drivers.

'Mineral demand' is often cited as a reason for renewed interest and pressure behind DSM in the Area (Calderon et al., 2024; Rosenberg, 2023). Notably, the International Energy Agency predicted six times more mineral inputs would be required in 2040 than today to reach net-zero globally by 2050 (IEA, 2022). However, we classified 'mineral demand' as a critical uncertainty rather than a key trend, based on a recent lack of consensus about future demand, indicated by the expert interviews. Mining proponents asserted that increasing consumerism and the energy transition will require a significant increase in minerals (Interview 1, 2024), while opponents expressed doubts about this need (Interview 2, 2024). One interviewee argued that emerging electric vehicle batteries do not require deep-sea minerals (Interview 3, 2024), and another stated there are "circular economy approaches that could be massively enhanced around product design and recycling and re-mining" (Interview 4, 2024). Therefore, the direction of mineral demand may have unpredictable impacts on DSM needs.

Another critical uncertainty is 'deep-sea research', which includes data on deep-sea ecology and mining impacts. Knowledge surrounding these factors is increasing but characterized by significant unknowns (Wang et al., 2023), which may influence DSM developments. Interviewees agreed on the presence of uncertainties surrounding deep-sea research, with a mining supporter acknowledging "we will never know everything" (Interview 1, 2024) and a mining opponent expressing concerns about the absence of clear environmental thresholds and definition of 'serious harm' (Interview 2, 2024). 'Speed of exploitation approval' is another critical uncertainty identified in interviews, as the rapidity of ISA mining approval is difficult to predict due to a lack of transparency in ISA proceedings, which may have implications for the thoroughness of DSM regulations. Some interviewees assured regulations would soon become finalized (Interview 6, 2024), while others believed negotiations will continue for some time (Interview 4, 2024). These three critical uncertainties will have varying impacts on the reality of DSM's future.

The two drivers of change characterized by the highest impact and uncertainty are 'environmental management' and 'benefit distribution', as they appear frequently in DSM literature, they lack notable consensus among stakeholders, and they concern the ISA's regulatory choices. 'Environmental management' includes the extent of regulations for, enforcement of, and compliance with environmental protection in the Area. This driver is characterized by high impact and uncertainty as, on one hand, ISA documents exemplify extensive mining regulations and commitments to environmental protection. Some interviews paralleled this perception, as one DSM proponent claimed the industry would be more transparent than other extractive industries and that "you will see a significant amount of detail in terms of what is required by a company" (Interview 1, 2024). Contrastingly, other interviewees stated that the ISA lacks adequate capacity for monitoring the Area (Interview 3, 2024) and that "there are going to be [regulatory] mistakes because there

Table 1
Document distribution.

Document type	Frequency
Academic literature	45
News/blog/website article	11
Government	7
NGO	8
International organization	11
International treaty	2

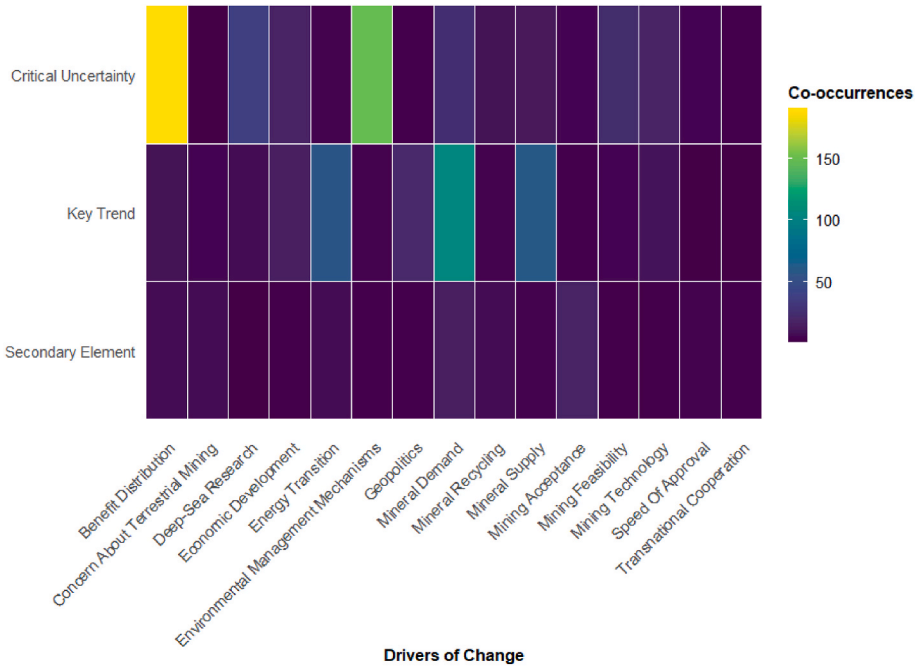

Fig. 1. Drivers of change frequencies.

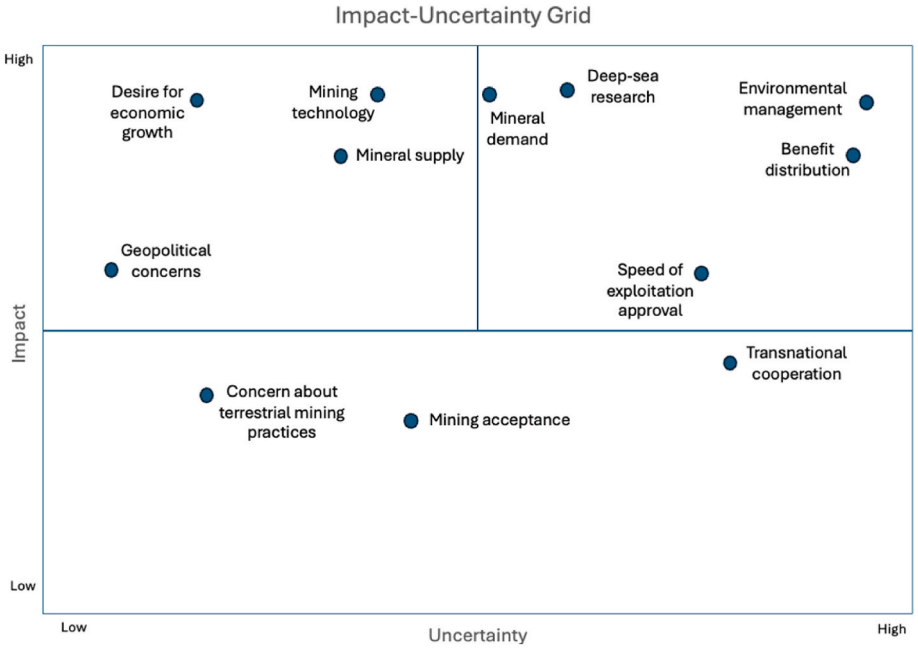

Fig. 2. Impact-uncertainty grid for DSM in the area.

always are" (Interview 2, 2024). This view is bolstered by arguments that ISA environmental standards are insufficient because deep-sea resources currently lack proper valuation (Interview 5, 2024). Therefore, future environmental management is surrounded by disagreement and is an important topic within DSM discourses.

'Benefit distribution' considers the level of stakeholder participation in decision-making, financial payment mechanisms, and non-monetary benefits that impact global equity. This driver is a critical uncertainty as one pro-mining interviewee acknowledged the ambiguity surrounding the exact implementation of a benefit-sharing mechanism, but "where there is no uncertainty is that that must happen" (Interview 1, 2024). Another stated that arguments for cultural benefits of the deep seabed are "not based on reason" (Interview 6, 2024) and thus create difficulties for executing benefit sharing. However, other interviewees question the economic profitability of mining and the subsequent extent of future benefits available for distribution (Interview 5, 2024). Additionally, one expressed concern that UNCLOS mandates for prioritizing the needs of developing states and disadvantaged groups are eroded by current ISA practices, especially considering transparency and stakeholder participation (Interview 4, 2024). Benefit sharing is thus another critical uncertainty determining how the CHM concept and global equity are upheld within DSM.

Other drivers of change classified as 'secondary elements' are important to scenario development but less impactful than key trends

and critical uncertainties. These include 'concern about terrestrial mining practices', which describes controversies surrounding practices within land-based mining (Interview 6, 2024; Roland-Holst, 2023); 'mining acceptance', which marks the extent of public support for DSM (Interview 1, 2024); and 'transnational cooperation', which includes the degree of multi-level collaboration among actors (Interview 4, 2024).

4.2. Plausible futures

We identified four plausible, explorative futures based on varying degrees of 'environmental management' and 'benefit distribution'. These scenarios, depicted in Fig. 3, are explained further by narratives about potential futures for DSM in international waters. We distinguished the scenarios by key descriptors (Table 2) such as industry structure and actor composition of governance.

4.2.1. Scenario I – Imperialist Abyss

In the 'Imperialist Abyss', DSM is marked by degraded ecosystems in the Area and unjust benefit and cost distributions amongst humankind. Higher demand for minerals needed to support increases in green energy leads to companies capitalizing on the growing metal market. Political tensions rise between China and the West, and countries bolster efforts to control their own sources of energy materials. The idea of economic gain, coupled with states' desires for development and energy security, spurs increasing pressure on the ISA to quickly finalize its exploitation regulations. Inequitable influence of stakeholders causes the interests of powerful actors to be prioritized at ISA proceedings (Morgera and Lily, 2022). This lack of engagement skews regulation development toward contractors' concerns—primarily short-term profit—and causes neglect of less influential groups, such as future generations and indigenous peoples. The race to stake "claims in the deep ocean for critical raw materials by the big power players" (Interview 3, 2024) enables those with more resources to dominate the industry. On paper, the initial Mining Code is "extremely robust" (Interview 1, 2024) compared to other extractive industries. However, the ISA's disproportionate attention on company profit and the novelty of deep-sea ecological research signifies a lack of thorough consideration for the ecological unknowns and costs of the industry. ISA working groups on environmental preservation and financial contract development are corrupted by collusion with private interests, leading to the eventual relaxation of exploitation regulations. As years pass, mining commences, although ecological research stagnates and environmental regulations regress. A decision about what constitutes environmental 'serious harm' remains dismissed due to slow progression toward consensus among ISA members (Pickens et al., 2024). Areas of Particular Environmental Interest (APEIs), initially created to protect areas and safeguard biodiversity, shrink over time as the ISA prioritizes profits.

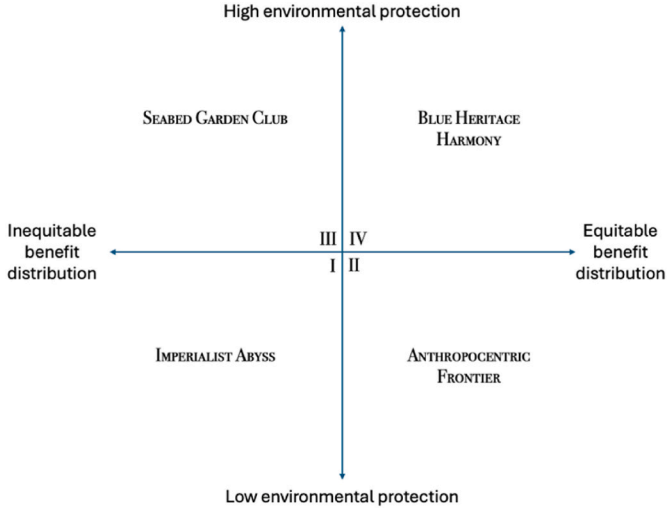

Fig. 3. 2 x 2 Scenario Matrix for DSM in the Area.

The UNCLOS provision to assist historically disadvantaged countries becomes a loophole for companies to claim sponsorship by developing states with poor regulatory structures, and subsequently dismiss environmental regulations. Downward competition between states leads to weakened environmental regulations, disincentives for financial redistribution, and increased political tensions (Feichtner, 2019). A few corporations dominate the industry by using sponsoring states as a mask, despite hoarding most of the benefits. A corrupted ISA requires a regressive contractor royalty rate and becomes a puppet for furthering powerful states' economic interests. Specifically, the Legal and Technical Commission (LTC) and Finance Committee include members involved with DSM companies. This skews regulations, contractor recommendations, and financial redistribution mechanisms to favor private interests. Therefore, negligible amounts of money remain available to share among developing and terrestrial mining states (Wilde et al., 2023). With the massive initial influx of rare minerals on the global markets, their prices plummet, disproportionately hurting terrestrial mining economies that depend on these resources.

Efforts to dominate the Area exacerbate conflicts between powerful countries. For example, the United States initiates DSM in the Area despite its failure to ratify UNCLOS and join the ISA (US CRS, 2023). This angers China and Russia (Interview 6, 2024), which increase efforts to secure control of the industry. Due to limited participation from youth, indigenous, and environmental groups, indirect benefits of deep seabeds, such as ecosystem services, capacity building, and knowledge sharing, are deemed too difficult to measure and are ignored. Indigenous communities with intangible deep-sea cultural heritage "don't have really a forum to make [their] voice[s] heard" (Interview 5, 2024) and must tolerate the idea that their ancestors at the seafloor will be "cut up by giant machines" (Interview 4, 2024). With environmental and social injustice, society's acceptance of DSM diminishes and protests at sea increase (IISD, 2024a). Rising transnational conflicts between private and public sectors lead to violent interactions and global unrest.

With insufficient environmental management, deep seabed minerals rapidly deplete. The industry progresses before non-invasive mining technologies develop and without adequate enforcement of environmental regulations. Without transnational cooperation, the ISA never develops a strategy for ensuring compliance and leaves contractor behavior unmonitored (Pickens et al., 2024). Environmental impacts, including sediment plumes and changes to mineral substrates, disrupt ecosystems dependent on deep-sea habitats (EASAC, 2023). Light and noise pollution disturb larger marine organisms and create ripple effects on broader marine ecosystems. Cumulative impacts of biodiversity loss and habitat degradation limit the ocean's ability to regulate climate, sequester carbon, and recycle nutrients (Levin et al., 2016). Without sufficient research, ecosystem degradation and species extinction cause unanticipated disruptions to food chains. Fish stocks deplete as nutrient cycling dwindles, preventing bottom-up sustenance of marine life (Jaeckel et al., 2023). This disrupts the livelihoods of fishermen (Roland-Holst, 2023) and contributes to strains on food resources.

Primary locations of seabed minerals, such as the CCZ, become barren, underwater wastelands overrun with machinery after being "exploited to the max" (Interview 5, 2024). No energy resources are safeguarded for future generations, nor are cultural heritage sites for indigenous and disadvantaged communities (Arato et al., 2024). Environmental benefits, such as biodiversity existence values and other ecosystem services, are sacrificed for short-term financial gains to serve actors from developed nations. Developing states experience insignificant economic gains due to a deficient payment mechanism, thereby widening global inequality. These nations become poorer and disproportionately suffer from long-term impacts of ecological degradation. The CHM concept is eroded, and DSM proceeds as an occurrence of harmful resource extraction marked by imperialism.

Table 2
Key descriptors of each DSM scenario.

Descriptors	Imperialist Abyss	Anthropocentric Frontier	Seabed Garden Club	Blue Heritage Harmony
Actor composition of governance	ISA dominated by private corporations & high-income states	Balance of influence from private sector, civil society, youth, indigenous groups, & states	ISA dominated by few private corporations & high-income states	Balanced of influence from private sector, civil society, youth, indigenous groups, & states
Governance characteristics	ISA prioritizes private interests & developed states; lack of transparency & stakeholder participation	High stakeholder participation within ISA proceedings; low enforcement of regulations	ISA prioritizes private interests; lack of participation; high enforcement of extensive regulations; precaution	High stakeholder participation; high enforcement of extensive regulations; precaution
Strategies of private actors	Seek sponsorship from developing states with weak regulatory structures; put pressure on ISA & investors; race to mine	Seek sponsorship from developing states; self-verification & monitoring	Collusion with elitist environmental groups; confidentiality; third-party verification & monitoring	Low presence in initial mining stages; small companies; more focus on circular economy initiatives
Industry structure	Monopolistic or oligopolistic; short-term profit prioritized	Perfect competition; short-term profit prioritized; involvement of Enterprise & private sector	Monopolistic or oligopolistic; long-term gains prioritized with discount rates	Financial & non-financial benefits prioritized; lower private sector presence
Extent of mining activity	Full production & exploitation; all technologies employed	Full production & exploitation; all technologies employed	Slow progression to production; moratorium until impacts are sufficiently assessed & necessary technology is developed	Moratorium until necessary technology & research is completed; staged mining approach
Global equity	Worsened; inequality widened & marginalized groups disregarded	Wealth gap shortened; equitable financial benefit distribution	Worsened; inequality widened & marginalized groups disregarded	Wealth gap shortened; equitable benefit distribution
Impact on deep seabed ecosystems	Severe degradation	Severe degradation	Minimal degradation	Minimal-to-no degradation

4.2.2. Scenario II – Anthropocentric Frontier

In this scenario, environmental protection is compromised by excessive focus on economic development. Participation within the ISA is high, providing developing states with greater influence. With increasing demand for energy minerals, state actions to utilize the resource-rich seabed exhibit an anthropocentric push to exploit the 'final frontier' (Cuyvers et al., 2018). After the invocation of the two-year rule, the ISA rushes to finalize exploitation regulations, despite significant gaps in environmental research. Environmental, youth, and indigenous groups enjoy representation at ISA proceedings, but discussions primarily focus on financial compensation for developing states rather than benefits associated with cultural and environmental preservation. Transnational cooperation is high, as players recognize opportunities for mutual benefits. DSM proceeds with minimal consideration for deep-sea ecosystems, justified by arguments that "the standards of living around the world are not equal, and that if we are to raise the standard of living, it will require more metal" (Interview 1, 2024). As years pass, the ISA continues accepting mining applications from companies and sponsoring countries. The high acceptance rate benefits developing states by providing economic opportunities and reducing geopolitical tensions through increased resource security. The ISA prioritizes compensating terrestrial mining countries for losses associated with increased competition, financing state capacity building, and redistributing money to developing countries (ISA, 2023b). While this supports financial benefit sharing, fewer resources are allocated toward monitoring and marine research. Countries enjoy increased affluence from DSM profits, leading to higher societal acceptance of the industry.

An increase of entrepreneurs follow the lead of DSM pioneers such as The Metals Company and AllSeas, making competition thrive. To hinder dominance by corporations, reserved areas are consistently set aside for later use by developing countries. Reserved areas are mining sites of similar economic value to those already explored by mining companies, allowing developing nations to avoid the costs of conducting research themselves (Jaeckel et al., 2016). DSM quickly becomes profitable despite increased competition, as ecosystem service values are neglected and compliance with environmental regulations is low. Companies seek sponsorship from developing states "because it's more difficult for the ISA to say no to a developing country that applies on behalf of a company" (Interview 3, 2024). Developing state sponsorship allows companies to operate in a relaxed regulatory environment, with low management costs (Roland-Holst, 2023).

The payment mechanism requires companies to pay a higher, progressive royalty to the ISA for redistribution (Van Nijen et al., 2019). This scheme provides sufficient compensation for the displacement of land-based mining economies, in addition to funding DSM capacity-building programs for developing countries. Many of these programs also assist terrestrial mining countries transition to DSM. The Enterprise, a body of the ISA for mining directly on behalf on humankind, is functional and operates to generate its own revenue for redistribution and capacity-building funds. With the unrestricted mineral extraction in seabeds, a significant portion of revenue is available for both developing states and future generations. This leads to higher incomes and increased consumption, and therefore a greater demand for technologies requiring deep seabed minerals. These outcomes reinforce the profitability of DSM and incentivize further exploitation.

Although environmental management ambition appears significant within the initial exploitation regulations (ISA, 2019), there is a lack of adaptive management and enforcement. Each mineral substrate is mined to provide the widest opportunities for resource extraction among interested parties. Without furthering scientific research and development of non-invasive technologies, the habitats containing these substrates are degraded. Countries initially proposing a moratorium relax their opposition as they recognize the industry's financial opportunities and perceive DSM as less harmful than terrestrial mining (Interview 6, 2024). ISA members agree on unrealistically high environmental thresholds to determine 'serious harm' and contractors lack pressure to collect extensive ecological data.

Comprehensive mechanisms to adjust environmental standards falter throughout the years, preventing successful ecological protection (Jaeckel, 2016). In the search for short-term profit and economic development, the unstudied impacts of DSM become realized before they can be remedied. This causes long-term climate impacts, disruptions to food chains, and the extinction of genetic resources for medical research (Miller et al., 2018). Despite this, a portion of DSM benefits is reinvested in geoengineering and farming technology to combat environmental catastrophes. Although non-human nature deteriorates, society preserves seabed benefits associated with indigenous cultures and intrinsic values of nature in museums and through storytelling. With no clear definition of CHM in UNCLOS (Jaeckel et al., 2016), the concept is interpreted to mean non-appropriation of resources, participation of developing states, and peaceful use. The initial "preservation for future generations" connotation of the concept only materializes in the conservation of deep-sea specimens in museums. The mineral needs of society are met for the next few decades, but ecological integrity is lost.

4.2.3. Scenario III – Seabed Garden Club

'Seabed Garden Club' involves high levels of environmental protection, but with inequitable benefit distribution. Increased mineral demand and energy security concerns create a profitable market for deep-sea minerals. However, an initial moratorium occurs based on calls from countries to prioritize research on the ecological impacts of mining and non-invasive technology (DSCC, 2024; France, 2022). This pause lasts several years, complemented by consistent revisions of the Mining Code that focus on adaptive management of environmental regulations. During the moratorium, companies applying for contracts focus investments on the development of better mining technology to adhere to increasingly stringent regulations. Once mining begins, the rigid application process to secure mining sites renders acceptance nearly impossible. The countries with existing exploration contracts in 2024 rapidly begin exploitation and sponsor companies from high-income countries with enough resources to ensure profitability while complying with regulations. This pattern contributes to an elitist industry structure dominated by rich actors, with low levels of stakeholder participation in ISA proceedings. The ISA lacks transparency and its committees, such as the LTC, are staffed by people associated with the commercial side of mining (Morgera and Lily, 2022). These committees prioritize application acceptance for a few companies sponsored by powerful countries and fail to enforce technology sharing with less developed states. This exclusivity limits the meaningful representation of humankind as required by UNCLOS.

Weak stakeholder participation within the ISA skews its interests to favor actors with vast resources and political power. Mining benefits are concentrated among countries with access to investments for advanced technologies, testing equipment, and staff. A body such as the Enterprise, designed to generate extra mining revenue for redistribution, remains dormant and non-functional, while private companies dominate the commercial aspect of DSM. Furthermore, advanced economies control the extracted minerals, embodying the "historic colonial paradigm once again of just the wealthiest people access[ing] the resources" (Interview 4, 2024). The contractor royalty rate is regressive, which limits the amount of funds available for redistribution among developing and terrestrial mining states. Concerns from African countries about this limitation are ignored, based on arguments that mining would otherwise lack economic viability (African Group, 2022).

Rather than creating a direct mechanism to financially assist disadvantaged states, the low royalties are pooled into a fund. However, instead of using the fund for capacity building or compensating terrestrial mining economies, it focuses on reimbursing states' past contributions to the ISA to eliminate the 'free-rider problem' of states joining mining later (Wilde et al., 2023). To appear in congruence with the ISA Strategic Plan to assist the development of poorer states (ISA, 2023b), a small portion of the fund is left to distribute financial benefits to states with the largest populations and lowest GDP per capita. This distribution is based on an underdeveloped equation in ISA Technical Study No. 31 (ISA, 2021). Additionally, the ISA designates remaining money to further marine scientific research. While this bolsters knowledge on deep-sea biodiversity and ecosystem services, it discretely and purposefully bars developing states from the industry through excessive application fees, unrealistic regulations, and restricted access to mining technology. Rather than reserving areas for later use by developing states, disproportionate weight is given to future generations through a high discount rate, which leads to excessively large APEIs. A few countries and corporations control the DSM industry, with the justification that further participation would compromise the Area's environmental integrity.

Although a few actors dominate the industry, the moratorium and limited access to mining lead to effective environmental management. The ISA prioritizes the UNCLOS mandate to protect the environment by requiring the most advanced mining technologies (ISA, 2019). These technologies are expensive, take years to develop, and are only accessible to high-income countries. The moratorium ensures the completion of extensive research on deep-sea ecosystems and provides enough time for this technological development. The machinery developed by companies such as Impossible Metals functions by hovering above the seabed, using a robotic arm to pluck nodules from the seafloor, and avoiding nodules with a significant amount of fauna (Fauna, 2023). As research continues, APEIs continuously grow, exploitation regulations are consistently revised, and Regional Environmental Management Plans (REMPs) required by contractors are reviewed often in accordance with adaptive management practices (IISD, 2024a). To avoid the full depletion of nodules, companies additionally harvest cobalt-rich crusts and seafloor massive sulfides following the development of appropriate technology and collection of sufficient environmental baseline data. Although the existence of fauna on each harvested substrate signifies some environmental impact, ecosystem services are incorporated into cost-benefit analyses and rigorous pre-mining impact assessments are completed to determine risk of 'serious harm' (Hitchin et al., 2023; Levin et al., 2016).

As previously acknowledged, contracts are nearly impossible to acquire due to expensive applications fees and strict environmental regulations. NGOs, such as Greenpeace, become elite environmental organizations that collude with private actors and harness DSM opposition as their "biggest cash cow" (Interview 6, 2024). Anti-mining states with large terrestrial mining industries contribute to this opposition to safeguard their economies, while claiming environmental concern (Interview 5, 2024). The resulting anti-mining culture allows high-income states to mine with discretion, while preventing other actors from entering the industry. This upholds the industry's exclusivity in the name of environmental preservation, despite hindering economic development for developing states. Any criticisms of inequity are met with arguments that exclusivity is necessary to uphold the CHM principle, based solely on the idea of the marine environment as cultural heritage for future generations and indigenous cultures. However, neither of these groups experience opportunities to voice their opinions in ISA discussions (Interview 5, 2024). This argument merely allows powerful actors to monopolize control of the industry and its financial benefits.

4.2.4. Scenario IV – Blue Heritage Harmony

'Blue Heritage Harmony' depicts a scenario with sufficient environmental protection and equitable benefit distribution. The ISA ensures the meaningful participation of all parties as prescribed by UNCLOS, leading to the protection of deep seabed ecosystems becoming a topic of utmost importance in negotiations. Additionally, the ISA develops a benefit distribution mechanism that prioritizes the needs of developing states, considers indigenous groups and youth, and includes both financial and non-monetary benefits. The energy transition, control of critical mineral supply chains by China, desire for economic growth, and abundance of minerals in the sea motivate countries to capitalize on DSM. However, there is no rush to exploitation. Calls for a moratorium are heeded by the ISA to prioritize deep-sea ecological research and the development of non-invasive mining technologies (DSCC, 2024; France, 2022). Transnational cooperation is high, contributing to the belief that a pause on DSM is necessary to agree on regulations that satisfy both interested states and environmentally motivated groups.

After a lengthy period without mining, comprehensive exploitation regulations are finalized in accordance with adaptive management practices. DSM is conducted collaboratively by the Enterprise and small mining companies to prevent unjust control by powerful conglomerates. Companies seeking to participate in DSM are simultaneously encouraged to direct investments toward circular economy approaches that enhance product design and focus on mineral recycling, thereby preventing economic dependency on DSM (Interview 4, 2024). The ISA functions transparently and employs credible, third-party verification organizations to minimize the risk of corruption when enforcing regulation compliance (Deberdt and James, 2024). The Enterprise becomes "a brilliant idea in terms of equity" (Interview 4, 2024), as it is fully

staffed by experts from developing countries and excels at data and technology sharing. Through the combination of revenue from small companies, a functional Enterprise, and a progressive royalty rate, sufficient funds are available to cover administrative costs, support terrestrial mining economies, provide capacity building, and promote marine scientific research (ISA, 2022a; 2023a). Equitable benefits are realized and environmental integrity is upheld, making societal mining acceptance high (Interview 1, 2024).

Exploitation regulations are slowly completed, which provides ample time to create an equitable benefit-sharing mechanism that considers groups included under the CHM principle. While the Enterprise functions as the primary contractor in the Area, additional contractors must meet certain application criteria. The contractors and sponsoring states with exploration licenses in 2024 commence mining when regulations are accepted, but new players must be under a certain development threshold according to multiple indicators, such as the Human Development Index, Vulnerability Indices, and GDP (Wilde et al., 2023). The strict access to mining sites and reservation of APEIs contributes to intergenerational equity by saving resources, ecological integrity, and the possibility of exploitation for future generations (Interview 2, 2024). Potential investors in DSM initially contact the Enterprise, which directs them to funding companies from developing countries interested in DSM as an alternative to sponsoring large corporations. This allows lower-income states to "benefit their people and benefit them for multiple generations" (Interview 1, 2024) by participating in the industry. Additionally, access to latest technologies and information allows lower-income nations to comply with strict environmental regulations more easily.

By limiting future industry participation, DSM remains viable and investors enjoy sufficient returns. Progressive royalties allow for contractors to profit in initial, uncertain phases of DSM to account for fluctuations in mineral prices. Royalties increase once the industry stabilizes to generate ample finances for the various funds (African Group, 2022; ISA, 2021; Li et al., 2021). The funds are used primarily for capacity building, knowledge and technology sharing, and training programs for companies from disadvantaged countries. A payment mechanism based on the ISA's Technical Study No. 31 (ISA, 2021) and suggestions by African countries (African Group, 2022) is created to reflect a combination of development indicators when determining payment shares (Wilde et al., 2023). With this, assessments are made to identify developing countries (excluding those directly profiting from DSM) that would benefit most from a higher share of funds. Exploitation occurs slowly and in specified time blocks determined by ISA members and consulted experts, which avoids "too many minerals too soon just flooding the markets" (Interview 2, 2024). This staged mining approach prevents economic damage from decreased mineral prices for States dependent on terrestrial mining. Therefore, the payment mechanism can focus on distributing funds to lower-income countries rather than compensation for potential economic damage.

To enable sufficient environmental protection, mining commences only after advanced technologies are accessible to developing states and proven to minimize environmental harm. These technologies use night vision to minimize bright lights, cause little-to-no noise pollution, prevent sediment plumes, and therefore avoid significant disturbance (Interview 4, 2024; Interview 5, 2024). Operations refrain from extracting minerals in seafloor massive sulfides and cobalt-rich crusts, unless there is a significant increase in mineral demand and sufficient environmental baseline data. This prevents displacing terrestrial mining economies and causing unnecessary environmental disturbance. Polymetallic nodules are harvested using a staged approach, in accordance with ecosystem-based management (Christiansen et al., 2022; Wang et al., 2023). These approaches prioritize periodic revisions of regulations by a working group on the preservation of the environment (Guilhon et al., 2023). Through this approach, an abundance of nodules remains on the ocean floor to avoid depletion of slow-developing substrates necessary for deep-sea ecosystems.

The ISA prioritizes environmental protection through extensive mining regulations and enforcing REMPs, which rely on third-party monitoring mechanisms and verification schemes rather than contractor self-monitoring (Interview 4, 2024; Deberdt and James, 2024). Data-sharing and collection methods enable fair and effective use of information, with "public funding that is not tied directly to an interest in mining" (Interview 3, 2024). Verification bodies frequently complete random inspections to assess whether activities meet regulations. APEIs are large, leaving more space protected than mined. Extensive research allows for continuous adaptation of exploitation regulations and updated information for cost-benefit analyses, with special consideration for indigenous environmental knowledge (Taga, 2023). Cost-benefit analyses include better valuation of externalities, deep-sea ecosystem services, and cultural values, which influences the amount of mining allowed (Interview 2, 2024; Brander and Gõni, 2023). If fluctuations in mineral demand, increases in ecosystem service values, or the release of new information on environmental impacts render mining unprofitable, the ISA mandates a pause on DSM activities. Nations thrive with secure mineral supplies, an abundance of green energy, new avenues for economic development, protection of ecological and cultural heritage, and the avoidance of cumulative climate impacts associated with deep-sea ecosystem degradation.

5. Discussion

The aim of scenario-building is not to identify equally likely future (s), but rather to anticipate a range of plausible trajectories based on expert and stakeholder input, allowing for better preparedness to each possible scenario (Mahmoud et al., 2009). In practice, future developments in DSM may contain elements from all four scenarios, depending on the evolution of each driver of change. While the actions of DSM stakeholders will play a role in shaping the industry's future and its impacts, several structural factors constrain their influence. Shifts in these structural drivers may present opportunities for those advocating a just and sustainable future for DSM, or, conversely, may lead to undesirable outcomes. This discussion begins by briefly surveying the constraints to action that transpire from our scenarios, before turning to policy recommendations on aspects that stakeholders can influence.

5.1. Challenges and opportunities for a sustainable DSM future

We structure our discussion of constraints to stakeholder action around the drivers of change at the root of our scenarios. We begin with the critical uncertainties at the center of this analysis, followed by other critical uncertainties and key trends.

First, concerning the environmental and benefit-sharing policies to be adopted at the ISA, recent developments provide a positive starting point to avoid extreme versions of 'Imperialist Abyss' or 'Anthropocentric Frontier'. Breakthroughs in related environmental negotiations including the adoption of the Biodiversity Beyond National Jurisdiction (BBNJ) Agreement as well as the Kunming-Montreal Global Biodiversity Framework (GBF) under the Convention on Biological Diversity (CBD) warrant careful optimism on environmental protection. Both instruments have implications for the biodiversity of the deep seabed and will have to be considered in ISA negotiations (Kim, 2024). Similarly, the successful inclusion of benefit-sharing measures for genetic resources in these two external examples shows that equity is in the zeitgeist of current environmental negotiations. In the context of DSM, these recent instruments pile up on the UNCLOS regime, which if effectively upheld, provides a solid basis for ISA delegates to strive for a form of 'Blue Heritage Harmony'. This includes a scenario variation where ISA members agree to reject mining indefinitely and beyond the period within this analysis. With this relatively solid bedrock of institutions, the main challenges to achieving 'Blue Heritage Harmony' lie in the implementation phase, as evidence suggests that international environmental agreements are often ineffectual and lack compliance

(Kellenberg and Levinson, 2014).

Second, although this study focuses on two drivers related to policy, other critical uncertainties are relatively beyond the control of decisionmakers. For example, uncertainties surrounding future mineral demand, based on factors such as mineral recycling and advancements in green technology batteries, will determine the economic feasibility of DSM in the Area (Dobush and Warner, 2024; IEA, 2022). Without viability, companies lack incentives to progress with mining (Interview 2, 2024). To explore the influence of policy choices in areas beyond national jurisdiction, this analysis developed scenarios by assuming the profitability of mining based on projections of demand by the International Energy Agency (IEA, 2022, 2023). Concerning the speed of exploitation approval, the pressures on the ISA from eager states and corporations pose a risk of DSM beginning without adequate environmental and redistributive regulations. The recent election of Leticia Reis de Carvalho of Brazil as Secretary-General, did, however, spark some hope that this new leadership would bring fresh momentum and help tackle issues of transparency and neutrality (IISD, 2024b). On the other hand, effective environmental rule adoption cannot take place without sufficient deep-sea ecological research. As long as these ecosystems are not thoroughly understood, the risks of DSM will remain unquantifiable.

Third, some key trends limit the action of stakeholders aiming for a just and responsible DSM industry. Geopolitical tensions, chiefly between China and the US and its allies, create a pressure for a "race to the bottom" in rushing exploitation as both sides seek increased control over the critical mineral supply chain. However, how the US will manage this factor while likely remaining outside of the UNCLOS framework for the foreseeable future is still uncertain. In the meantime, China remains the strongest voice at the ISA arguing for the quick commencement of DSM (Kardon and Camacho, 2023). Overall, there is a stark contrast between a nominally ambitious existing framework on both environmental and equity-related matters, and structural constraints to its implementation. In this context, alternative scenarios provide policymakers with more reflexivity, allowing for early contingency action and recognition of opportunities when drivers of change evolve (Cairns and Wright, 2018).

5.2. Policy recommendations

When deciding on a course of action for DSM, global policymakers should carefully consider the challenges identified above to improve chances of reaching 'Blue Heritage Harmony'. Although this scenario represents an idealized future rather than a pragmatic goal, striving to emulate it should produce better outcomes than business-as-usual.

To enforce effective environmental protection, regulations and goals should be sufficiently aligned with relevant international environmental agreements such as the CBD and the BBNJ Agreement, as a report recently commissioned by the ISA recognized (ISA, 2024). To do so, the ISA should impose an initial moratorium on DSM to prioritize ample research and technological advancements, followed by the establishment of an Environmental Strategy for the Area to define its objectives (Ginzky et al., 2020). This would provide opportunities to avoid serious impacts to the environment and achieve coherence with existing international obligations (Singh and Jaeckel, 2024). However, the complex structure of the ISA and its numerous member states with diverse interests suggests consensus on these issues will not be reached easily. In the meantime, willing states should set an example by adopting moratoriums on DSM in national waters until the impacts are well understood.

Additionally, a staged, ecosystem approach based on adaptive management, outlined in 'Blue Heritage Harmony', should be better defined and implemented within ISA goals and regulations (Christiansen et al., 2022). This would entail the exploitation of few, small mining sites at a time to protect biodiversity and resources for future generations, while acquiring more information about the Area (Niner et al., 2018; Thompson et al., 2018). By mining in stages, the ISA can prioritize the improvement of REMPs, standardization of technologies and data analysis, and more accessible databases for sharing information before deep seabeds are fully exploited (Guilhon et al., 2023). This way, DSM activities would harmonize environmental protection and equity rather than prioritizing one over the other, as is done in 'Seabed Garden Club' and 'Anthropocentric Frontier'. To increase accuracy of impact analyses and planning, implementing an ecosystem approach to management should also include consideration of the interconnectedness of deep seabeds with water column ecosystems, valuation of ecosystem services in cost-benefit analyses (Brander and Gõni, 2023), clear threshold establishment (Hitchin et al., 2023), better definitions of 'serious harm' (Levin et al., 2016), and recognition of nature as a non-human actor (Campbell et al., 2022).

To ensure compliance with environmental regulations at sea, independent third-party auditors should complete unexpected inspections of mining sites, in combination with the use of monitoring technology (Deberdt and James, 2024; Thompson et al., 2018). The ISA should also promote an increase in studies of the deep sea, led by research institutions not affiliated with corporate interests in DSM. States and organizations that wish to protect seabed ecosystems should pave the way by investing in research on the national level. These studies, accompanied by better incorporation of indigenous knowledge (Tilot et al., 2021), would bolster the adequacy and comprehensiveness of environmental protection in the Area. Such initiatives would help achieve the goals of 'Blue Heritage Harmony' by increasing meaningful participation and subsequently improving the quality of management.

Ensuring equitable benefit and cost distribution requires ISA policy choices tailored to improvements in participation and transparency. The current status of participation within the ISA includes the representation of member states and the opportunity for non-state entities such as NGOs, civil society groups, and non-member states to enjoy observer status at proceedings, as well as periodic stakeholder consultations (ISA, 2020). However, the ISA should engage in proactive consultation with a wider group of stakeholders beyond those already involved, especially indigenous peoples (Ardron et al., 2023; Campbell et al., 2022). To achieve the representation exhibited in 'Blue Heritage Harmony', interested stakeholders must be informed about decision-making processes within the ISA, even if they cannot legally vote on decisions (Morgera and Lily, 2022). This effort would require the ISA to improve the timeliness and accessibility of proceeding information through webinars and published online documents (Mascarenhas, 2024; Menini et al., 2022). On the scientific front, the ISA has made significant progress in equity by providing online access to data collected by contractors with the establishment of its DeepData database in 2019. It should make sure to pursue this effort by integrating this tool with the BBNJ Agreement's Clearing-House Mechanism. This is especially important considering the ambiguities that remain concerning each institution's jurisdiction on seabed marine genetic resources (ISA, 2024), which also involve a benefit-sharing scheme. Additionally, the ISA must bolster its efforts in public outreach to ensure representation beyond contractors and scientists. Enhancing stakeholder participation would widen the knowledge base for environmental management, while simultaneously ensuring the degree of equity necessary for developing a comprehensive benefit-sharing mechanism (Van Nijen et al., 2019).

6. Conclusion

This paper's scenario analysis identifies the drivers of change of DSM in international waters and their potential implications for the future. With the invocation of the two-year rule pushing for regulation finalization, the ISA's decisions in the next few years will have lasting impacts on the trajectory of DSM for the coming decades. That said, the complexity of ecological systems and global governance presents difficulties for effectively governing the Area to uphold global justice and protect the environment.

The consequences of historical resource extraction and energy use have exposed the dangers of exploiting non-renewable resources

without consideration of environmental implications. Failures to anticipate climate change associated with fossil fuel extraction has led to the search for other, cleaner forms of energy. However, in a feedback loop fashion, society is now recognizing problems associated with more renewable energy such as the environmental risks of DSM. With the lack of available knowledge on deep-sea ecosystems and potential DSM impacts, reluctance to mine the seabed grows within civil society. On the other hand, high-income countries have historically benefitted from the exploitation of oil and gas without sufficient consideration for the impacts on future generations. Therefore, many developing countries seek similar opportunities through DSM. This dilemma contributes to discussions around the possibility of DSM and the correct way to move forward.

The scenarios presented in this paper do not aim for perfect accuracy on how the future may develop. However, they intuitively demonstrate consequences associated with an international DSM regime that does not emphasize constant improvement and careful consideration. Although 'Anthropocentric Frontier' prioritizes current generations by providing access to valuable resources, it compromises the health of future generations based on unpredictable consequences of deep-sea degradation. 'Seabed Garden Club' considers future generations and environmental interests by preserving deep-sea areas, but neglects UNCLOS' mandate to assist developing states. This juxtaposition reveals the risks of upholding one dimension at the expense of the other and signifies a need for DSM policymakers to weigh the impacts of their decisions on both ecological integrity and global equity. These scenarios may serve as a tool for doing so.

The policy recommendations presented in the discussion must be bolstered by further research into mechanisms for meaningful participation, ecological data, mining impacts, and institutional deficiencies, to ensure the DSM regime serves humanity and non-human nature effectively. Additionally, scholars should focus on identifying and developing broader alternatives to mining, such as mineral recycling in a circular economy and decreasing energy demands. The ISA, states, and industry stakeholders currently stand at a crossroads with regards to the future of DSM. Whether it will be governed appropriately for the needs of the Earth and its inhabitants will largely depend on the decisions that are made on the key challenges of environmental management and benefit sharing.

CRediT authorship contribution statement

Aurora Cato: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Philippe Evoy:** Writing – review & editing, Visualization, Supervision, Resources, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to thank Pauline Pic, as well as the anonymous reviewers and editors for their constructive comments, which have allowed us to significantly improve this article. Philippe Evoy acknowledges the Fonds de recherche du Québec (FRQ) for its financial support (grant 320467).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esg.2025.100249.

Data availability

Data will be made available on request.

References

African Group, 2022. African group submission on the payment regime for Deep-sea Mining in the area. https://www.isa.org.jm/wp-content/uploads/2022/12/African_Group_Submission_Payment_Regime.pdf.

Alcamo, J., 2008. In: Environmental Futures: the Practice of Environmental Scenario Analysis, first ed., vol. 2. Elsevier Science.

Arato, J., Jaeckel, A., Lixinski, L., 2024. On the Cultural Stakes of Deep Seabed Mining, vol. 118, pp. 67–71. https://doi.org/10.1017/aju.2024.9.

Ardron, J.A., Ruhl, H.A., Jones, D.O.B., 2018. Incorporating transparency into the governance of deep-seabed mining in the Area beyond national jurisdiction. Mar. Pol. 89, 58–66. https://doi.org/10.1016/j.marpol.2017.11.021.

Ardron, J., Lily, H., Jaeckel, A., 2023. Public participation in the governance of deep-seabed mining in the Area. In: Rayfuse, R., Jaeckel, A., Klein, N. (Eds.), Research Handbook on International Marine Environmental Law. Edward Elgar Publishing, pp. 361–384. https://doi.org/10.4337/9781789909081.00026.

Börjeson, L., Höjer, M., Dreborg, K.-H., Ekvall, T., Finnveden, G., 2006. Scenario types and techniques: towards a user's guide. Futures 38 (7), 723–739. https://doi.org/10.1016/j.futures.2005.12.002.

Brander, L., Gōni, V.G., 2023. Report on the Value of Ecosystem Services and Natural Capital of the Area. Institute for Environmental Studies (IVM) and Institute for Physical Geography and Landscape Ecology. https://www.isa.org.jm/wp-content/uploads/2023/06/Report-on-Valuation-of-ecosystem-services.pdf.

Cairns, G., Wright, G., 2018. Scenario Thinking. Springer International Publishing. https://doi.org/10.1007/978-3-319-49067-0.

Calderon, J.L., Smith, N.M., Bazilian, M.D., Holley, E., 2024. Critical mineral demand estimates for low-carbon technologies: what do they tell us and how can they evolve? Renew. Sustain. Energy Rev. 189, 113938. https://doi.org/10.1016/j.rser.2023.113938.

Campbell, L.M., Fail, R., Horan, R., Acton, L., Blackwatters, J.E., Garcia Lozano, A., Gill, D., Gray, N., Gruby, R., Melvin, E., Murray, G., Wiehe, E., 2022. Architecture and agency for equity in areas beyond national jurisdiction. Earth System Governance 13, 100144. https://doi.org/10.1016/j.esg.2022.100144.

Christiansen, S., Durussel, C., Guilhon, M., Singh, P., Unger, S., 2022. Towards an ecosystem approach to management in areas beyond national jurisdiction: REMPs for deep seabed mining and the proposed BBNJ instrument. Front. Mar. Sci. 9. https://doi.org/10.3389/fmars.2022.720146.

Conde, M., Mondré, A., Peters, K., Steinberg, P., 2022. Mining questions of 'what' and 'who': deepening discussions of the seabed for future policy and governance. Maritime Studies 21 (3), 327–338. https://doi.org/10.1007/s40152-022-00273-2.

Cuyvers, L., Berry, W., Kristina, G., Torsten, T., Caroline, W., 2018. Deep Seabed Mining: A Rising Environmental Challenge, first ed. IUCN, International Union for Conservation of Nature. https://doi.org/10.2305/IUCN.CH.2018.16.en.

Dean, M., 2019. Scenario planning: a literature review. https://doi.org/10.13140/RG.2.2.12629.24802.

Deberdt, R., James, C.B.G., 2024. Self-governance at depth: the international seabed authority and verification culture of the deep-sea mining industry. Resour. Policy 89, 104577. https://doi.org/10.1016/j.resourpol.2023.104577.

Dobush, B.-J., Warner, M., 2024. Deep Sea mining Isn't Worth the risk. The Ocean Foundation 46. https://oceanfdn.org/wp-content/uploads/2024/02/dsm-finance-brief-2024.pdf.

DSCC, 2024. Voices calling for a moratorium. Deep Sea Conservation Coalition. https://deep-sea-conservation.org/solutions/no-deep-sea-mining/momentum-for-a-moratorium/governments-and-parliamentarians/.

EASAC, 2023. *Deep-sea Mining: Assessing Evidence on Future Needs and Environmental Impacts* (Deep-Sea Mining. European Academies' Science Advisory Council, p. 25.

Enserink, B., Bots, P., Daalen, E. van, Hermans, L., Kortmann, R., Koppenjan, J., Kwakkel, J., Ruijgh, T., Thissen, W., Slinger, J., 2022. Policy analysis of multi-actor systems. In: TU Delft OPEN Textbooks, second ed. TU Delft OPEN Textbooks. https://doi.org/10.5074/T.2022.004.

Fauna, Flora, 2023. Update to 'An Assessment of the Risks and Impacts of Seabed Mining on Marine Ecosystems. Cambridge UK. www.fauna-flora.org.

Feichtner, I., 2019. Sharing the Riches of the Sea: the redistributive and fiscal dimension of deep seabed exploitation. Eur. J. Int. Law 30 (2), 601–633. https://doi.org/10.1093/ejil/chz022.

France, 2022. Declaration by France to the international seabed authority. https://www.isa.org.jm/wp-content/uploads/2022/12/DECLARATION-FRANCE-TO-THE-ISA.pdf.

Ginzky, H., Singh, P.A., Markus, T., 2020. Strengthening the International Seabed Authority's knowledge-base: Addressing uncertainties to enhance decision-making. Mar. Pol. 114, 103823. https://doi.org/10.1016/j.marpol.2020.103823.

Glasby, G.P., 2000. Lessons learned from Deep-Sea Mining. Science 289 (5479), 551–553. https://doi.org/10.1126/science.289.5479.551.

Glasby, G.P., 2002. Deep seabed mining: past failures and future prospects. Mar. Georesour. Geotechnol. 20 (2), 161–176. https://doi.org/10.1080/03608860290051859.

Glover, A.G., Smith, C.R., 2003. The deep-sea floor ecosystem: current status and prospects of anthropogenic change by the year 2025. Environ. Conserv. 30 (3), 219–241. https://doi.org/10.1017/S0376892903000225.

Guilhon, M., Xavier, L.Y., von Pogrell, L., Singh, P., Christiansen, S., Turra, A., 2023. Ecosystem-based Management through the lenses of International Seabed Authority stakeholders: current status, implications, and opportunities for the deep-sea mining regime in the Area. Front. Mar. Sci. 10. https://doi.org/10.3389/fmars.2023.1139396.

Hitchin, B., Smith, S., Kröger, K., Jones, D., Jaeckel, A., Mestre, N., Ardron, J., Escobar, E., van der Grient, J., Amaro, T., 2023. Thresholds in deep-seabed mining: a primer for their development. Mar. Pol. 149, 105505. https://doi.org/10.1016/j.marpol.2023.105505.

IEA, 2022. Mineral Requirements for Clean Energy Transitions – the Role of Critical Minerals in Clean Energy Transitions – Analysis. International Energy Agency. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/mineral-requirements-for-clean-energy-transitions.

IEA, 2023. World Energy Outlook 2023. International Energy Agency.

IEA. (n.d.). Critical Minerals – Topics. International Energy Agency. https://www.iea.org/topics/critical-minerals.

IISD, 2024a. Summary report 18–29 March 2024. IISD Earth Negotiations Bulletin. http://enb.iisd.org/international-seabed-authority-isa-council-29-1-summary.

IISD, 2024b. Summary report 15 july–2 August 2024. IISD Earth Negotiations Bulletin. https://enb.iisd.org/sites/default/files/2024-08/enb25256e.pdf.

IPBES, 2019. Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services. Zenodo. https://doi.org/10.5281/zenodo.3553579.

IPCC, 2023. Summary for policymakers. In: Lee, H., Romero, J. (Eds.), Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, pp. 1–34. https://doi.org/10.59327/IPCC/AR6-9789291691647.001.

ISA, 2019. Draft regulations on exploitation of mineral resources in the Area. https://www.isa.org.jm/wp-content/uploads/2022/06/isba_25_c_wp1-e_0.pdf.

ISA, 2020. Communications and stakeholder engagement strategy (zero draft). https://www.isa.org.jm/wp-content/uploads/2022/03/Draft_Comms_and_Stakeholder_Engagement_Strategy.pdf.

ISA, 2021a. ISA technical study No. 31: equitable sharing of financial and other economic benefits from deep-seabed mining. https://equitablesharing.isa.org.jm/Documents/ISA-Technical-Study-31.pdf.

ISA, 2022a. Policy Brief: equitable sharing of financial and other economic benefits from Deep-Sea Mining. https://www.isa.org.jm/wp-content/uploads/2022/06/policy_brief_benefit_sharing_01_2022-1.pdf.

ISA, 2022b. Exploration areas—international seabed authority. https://www.isa.org.jm/exploration-contracts/exploration-areas/.

ISA, 2023a. Partnership fund—international seabed authority. https://www.isa.org.jm/isa-partnership-fund/.

ISA, 2023b. Consideration for adoption of the strategic plan of the authority for the Period 2024-2028. https://www.isa.org.jm/wp-content/uploads/2023/07/ISBA_28_A_7.pdf.

ISA, 2024. A Review of the Contribution of ISA to the Objectives of the 2023 Agreement under UNCLOS on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction. International Seabed Authority. https://www.isa.org.jm/wp-content/uploads/2024/06/The_contribution_of_ISA_to_the_BBNJ_objectives.pdf.

Jaeckel, A., 2016. Deep seabed mining and adaptive management: the procedural challenges for the International Seabed Authority. Mar. Pol. 70, 205–211. https://doi.org/10.1016/j.marpol.2016.03.008.

Jaeckel, A., Ardron, J.A., Gjerde, K.M., 2016. Sharing benefits of the common heritage of mankind – is the deep seabed mining regime ready? Mar. Pol. 70, 198–204. https://doi.org/10.1016/j.marpol.2016.03.009.

Jaeckel, A., Harden-Davies, H., Amon, D.J., van der Grient, J., Hanich, Q., van Leeuwen, J., Niner, H.J., Seto, K., 2023. Deep seabed mining lacks social legitimacy. Npj Ocean Sustainability 2 (1). https://doi.org/10.1038/s44183-023-00009-7. Article 1.

Kardon, I.B., Camacho, S., 2023. Why China, Not the United States, Is Making the Rules for Deep-Sea Mining. Carnegie Endowment for International Peace. https://carnegieendowment.org/research/2023/12/why-china-not-the-united-states-is-making-the-rules-for-deep-sea-mining?lang=en.

Kellenberg, D., Levinson, A., 2014. Waste of effort? International environmental agreements. Journal of the Association of Environmental and Resource Economists 1 (1/2), 135–169. https://doi.org/10.1086/676037.

Kim, R.E., 2017. Should deep seabed mining be allowed? Mar. Pol. 82, 134–137. https://doi.org/10.1016/j.marpol.2017.05.010.

Kim, R.E., 2024. The likely impact of the BBNJ Agreement on the architecture of ocean governance. Mar. Pol. 165, 106190. https://doi.org/10.1016/j.marpol.2024.106190.

Kung, A., Svobodova, K., Lèbre, E., Valenta, R., Kemp, D., Owen, J.R., 2021. Governing deep sea mining in the face of uncertainty. J. Environ. Manag. 279, 111593. https://doi.org/10.1016/j.jenvman.2020.111593.

Kurzweil, R., 2004. The law of accelerating returns. In: Teuscher, C. (Ed.), Alan Turing: Life and Legacy of a Great Thinker. Springer, pp. 381–416. https://doi.org/10.1007/978-3-662-05642-4_16.

Levin, L.A., Mengerink, K., Gjerde, K.M., Rowden, A.A., Van Dover, C.L., Clark, M.R., Ramirez-Llodra, E., Currie, B., Smith, C.R., Sato, K.N., Gallo, N., Sweetman, A.K., Lily, H., Armstrong, C.W., Brider, J., 2016. Defining "serious harm" to the marine environment in the context of deep-seabed mining. Mar. Pol. 74, 245–259. https://doi.org/10.1016/j.marpol.2016.09.032.

Levin, L.A., Amon, D.J., Lily, H., 2020. Challenges to the sustainability of deep-seabed mining. Nat. Sustain. 3 (10). https://doi.org/10.1038/s41893-020-0558-x. Article 10.

Li, Y., Liu, C., Su, S., Li, M., Liu, S., 2021. Analysis of the effect of payment mechanism on exploitation of polymetallic nodules in the area. Minerals 11 (2). https://doi.org/10.3390/min11020221. Article 2.

Mahmoud, M., Liu, Y., Hartmann, H., Stewart, S., Wagener, T., Semmens, D., Stewart, R., Gupta, H., Dominguez, D., Dominguez, F., Hulse, D., Letcher, R., Rashleigh, B., Smith, C., Street, R., Ticehurst, J., Twery, M., van Delden, H., Waldick, R., et al., 2009. A formal framework for scenario development in support of environmental decision-making. Environ. Model. Software 24 (7), 798–808. https://doi.org/10.1016/j.envsoft.2008.11.010.

Mascarenhas, V., 2024. Assessment of Stakeholder Options to Participate in Disputes over Seabed Mining, vol. 118, pp. 98–102. https://doi.org/10.1017/aju.2024.13.

Meadows, D.H., Meadows, D.L., Randers, J., Behrens, W., 1972. The Limits to growth; a report for the Club of Rome's project on the predicament of mankind. Universe Books.

Menini, E., Chakraborty, A., Roady, S.E., 2022. Public participation in seabed mining in areas beyond national jurisdiction: lessons learned from national regulators in the terrestrial mining sector. Mar. Pol. 146, 105308. https://doi.org/10.1016/j.marpol.2022.105308.

MIDAS, 2016. Managing impacts of Deep Sea resource exploitation. https://www.eu-midas.net/sites/default/files/downloads/MIDAS_research_highlights_low_res.pdf.

Mietzner, D., Reger, G., 2005. Advantages and disadvantages of scenario approaches for strategic foresight. Int. J. Technol. Intell. Plann. 1 (2), 220–239. https://doi.org/10.1504/IJTIP.2005.006516.

Miller, K.A., Thompson, K.F., Johnston, P., Santillo, D., 2018. An overview of seabed mining including the current state of development, environmental impacts, and knowledge gaps. Front. Mar. Sci. 4. https://doi.org/10.3389/fmars.2017.00418.

Morgera, E., Lily, H., 2022. Public participation at the International Seabed Authority: an international human rights law analysis. Review of European, Comparative & International Environmental Law 31 (3), 374–388. https://doi.org/10.1111/reel.12472.

Nandan, S.N., Lodge, M.W., 2002. The development of the regime for deep seabed mining. In: Rosenne, S. (Ed.), International Seabed Authority.

Niner, H.J., Ardron, J.A., Escobar, E.G., Gianni, M., Jaeckel, A., Jones, D.O.B., Levin, L.A., Smith, C.R., Thiele, T., Turner, P.J., Van Dover, C.L., Watling, L., Gjerde, K.M., 2018. Deep-Sea mining with No net loss of biodiversity—an impossible aim. Front. Mar. Sci. 5. https://doi.org/10.3389/fmars.2018.00053.

Oteros-Rozas, E., Martín-López, B., Daw, T., Bohensky, E., Butler, J., Hill, R., Martin-Ortega, J., Quinlan, A., Ravera, F., Ruiz-Mallén, I., Thyresson, M., Mistry, J., Palomo, I., Peterson, G., Plieninger, T., Waylen, K., Beach, D., Bohnet, I., Hamann, M., et al., 2015. Participatory scenario planning in place-based social-ecological research: insights and experiences from 23 case studies. Ecol. Soc. 20 (4). https://doi.org/10.5751/ES-07985-200432.

Pickens, C., Lily, H., Harrould-Kolieb, E., Blanchard, C., Chakraborty, A., 2024. From what-if to what-now: status of the deep-sea mining regulations and underlying drivers for outstanding issues. Mar. Pol., 105967 https://doi.org/10.1016/j.marpol.2023.105967.

Poli, R., 2017. Introduction to Anticipation Studies, vol. 1. Springer International Publishing. https://doi.org/10.1007/978-3-319-63023-6.

Ramirez, R., Wilkinson, A., 2014. Rethinking the 2×2 scenario method: grid or frames? Technol. Forecast. Soc. Change 86, 254–264. https://doi.org/10.1016/j.techfore.2013.10.020.

Ranganathan, S., 2014. Strategically Created Treaty Conflicts and the Politics of International Law, first ed. Cambridge University Press. https://doi.org/10.1017/CBO9781107338005.

Roland-Holst, R.J., 2023. Exploiting the Deep Seabed for the Benefit of Humankind: A Universal Ideology for Sustainable Resource Development or a False Necessity? Cambridge University Press. https://doi.org/10.1017/S092215652300064X.

Rosenberg, D., 2023. The legal Fight over Deep-Sea Resources Enters a new and uncertain phase. EJIL: Talk. https://www.ejiltalk.org/the-legal-fight-over-deep-sea-resources-enters-a-new-and-uncertain-phase/.

Schwartz, P., 1996. The Art of the Long View: Planning for the Future in an Uncertain World. Crown.

Singh, P., Jaeckel, A., 2024. Undermining by Mining? Deep Seabed Mining in Light of International Marine Environmental Law, vol. 118, pp. 72–77. https://doi.org/10.1017/aju.2024.8.

Sparenberg, O., 2019. A historical perspective on deep-sea mining for manganese nodules, 1965–2019. Extr. Ind. Soc. 6 (3), 842–854. https://doi.org/10.1016/j.exis.2019.04.001.

Sus, M., Hadeed, M., 2020. Theory-infused and policy-relevant: on the usefulness of scenario analysis for international relations. Contemp. Secur. Policy 41 (3), 432–455. https://doi.org/10.1080/13523260.2020.1730055.

Swart, R.J., Raskin, P., Robinson, J., 2004. The problem of the future: sustainability science and scenario analysis. Glob. Environ. Change 14 (2), 137–146. https://doi.org/10.1016/j.gloenvcha.2003.10.002.

Sweetman, A.K., Smith, A.J., De Jonge, D.S.W., Hahn, T., Schroedl, P., Silverstein, M., Andrade, C., Edwards, R.L., Lough, A.J.M., Woulds, C., Homoky, W.B., Koschinsky, A., Fuchs, S., Kuhn, T., Geiger, F., Marlow, J.J., 2024. Evidence of dark oxygen production at the abyssal seafloor. Nat. Geosci. 17 (8), 737–739. https://doi.org/10.1038/s41561-024-01480-8.

Taga, R., 2023. The Facilitator's fourth revised draft text on Parts IV and VI and related Annexes. https://www.isa.org.jm/wp-content/uploads/2023/10/Facilitators-fourth-revised_text-16OCT23.pdf.

Thompson, K.F., Miller, K.A., Currie, D., Johnston, P., Santillo, D., 2018. Seabed mining and approaches to governance of the deep seabed. Front. Mar. Sci. 5, 480. https://doi.org/10.3389/fmars.2018.00480.

Tilot, V., Willaert, K., Guilloux, B., Chen, W., Mulalap, C.Y., Gaulme, F., Bambridge, T., Peters, K., Dahl, A., 2021. Traditional dimensions of seabed resource management in the context of Deep Sea Mining in the pacific: learning from the socio-ecological interconnectivity between island communities and the Ocean realm. Front. Mar. Sci. 8. https://doi.org/10.3389/fmars.2021.637938.

US CRS, 2023. Sea Mining: Frequently Asked Questions, R47429. Congressional Research Service, p. 14. https://crsreports.congress.gov/product/pdf/R/R47429.

van der Heijden, K., 2005. Scenarios: the Art of Strategic Conversation, second ed. John Wiley & Sons, Ltd.

Van Nijen, K., Passel, S., Brown, C., Lodge, M., Segerson, K., Squires, D., 2019. The development of a payment regime for Deep Sea Mining activities in the area through stakeholder participation. Int. J. Mar. Coast. Law 34, 1–31. https://doi.org/10.1163/15718085-13441100.

Vervoort, J.M., Thornton, P.K., Kristjanson, P., Förch, W., Ericksen, P.J., Kok, K., Ingram, J.S.I., Herrero, M., Palazzo, A., Helfgott, A.E.S., Wilkinson, A., Havlík, P., Mason-D'Croz, D., Jost, C., 2014. Challenges to scenario-guided adaptive action on food security under climate change. Glob. Environ. Change 28, 383–394. https://doi.org/10.1016/j.gloenvcha.2014.03.001.

Vogler, J., 2012. Global commons revisited. Global Policy 3 (1), 61–71. https://doi.org/10.1111/j.1758-5899.2011.00156.x.

Wang, J., Jiang, W., Wang, C., Liu, D., 2023. Taking precautionary approaches to the governance of commercial deep seabed mining: law-making of international seabed authority and multi-subject participation. Sustainability 15 (8). https://doi.org/10.3390/su15086414. Article 8.

Wilde, D., Lily, H., Craik, N., Chakraborty, A., 2023. Equitable sharing of deep-sea mining benefits: more questions than answers. Mar. Pol. 151, 105572. https://doi.org/10.1016/j.marpol.2023.105572.

Wilkinson, A., Kupers, R., Mangalagiu, D., 2013. How plausibility-based scenario practices are grappling with complexity to appreciate and address 21st century challenges. Technol. Forecast. Soc. Change 80 (4), 699–710. https://doi.org/10.1016/j.techfore.2012.10.031.

Willaert, K., 2020. Public participation in the context of deep sea mining: luxury or legal obligation? Ocean Coast Manag. 198, 105368. https://doi.org/10.1016/j.ocecoaman.2020.105368.

Worm, B., Barbier, E.B., Beaumont, N., Duffy, J.E., Folke, C., Halpern, B.S., Jackson, J.B. C., Lotze, H.K., Micheli, F., Palumbi, S.R., Sala, E., Selkoe, K.A., Stachowicz, J.J., Watson, R., 2006. Impacts of biodiversity loss on ocean ecosystem services. Science 314 (5800), 787–790. https://doi.org/10.1126/science.1132294.

Yap, X.-S., Janssen, M.A., Aganaba, T., Tutton, R., Korpershoek, K., Profitiliotis, G., Rabitz, F., Subbiah, M.S., Wagenknecht, L., 2023. Four alternative scenarios of commons in space: prospects and challenges. Int. J. Commons 17 (1), 390–410. https://doi.org/10.5334/ijc.1272.