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Battery metals from the deep sea: using industrial ecology for comparative analysis of impacts with terrestrial mining

Saleem H. Ali, †‡*[abc] Alexander Gilbert†‡[d] and Aiden Kuo‡[e]

Growing global demand for industrial metals is driving emergent interest by companies and countries in mining minerals from the deep seabed, specifically to develop batteries. Oceanic mining companies have particularly noted that polymetallic nodules with manganese, nickel, cobalt and copper are well-suited for the "battery revolution." However, there is substantial uncertainty regarding the environmental and social consequences of expanding human industrial activities to the fragile seabed and related ecosystems. Industrial ecology tools can support decision-making related to oceanic mineral exploitation by mitigating this uncertainty and providing comparisons to terrestrial exploitation. Major tools developed for terrestrial systems, such as design for the environment, dematerialization, and life cycle analysis, can supplement conventional environmental impact assessments. However, research on their application from a systems perspective across terrestrial and oceanic environments to date has been limited. Such tools can inform emerging resource governance mechanisms for national and international waters. Broader efforts to reduce global economic resource intensity can also reduce demand for deep sea minerals. Once there are enough metals in product stocks for recycling within their maximum available life, a transition to a circular economy for battery metals may be possible.

Environmental significance

This paper proposes a systems-level approach to considering the environmental costs and benefits of terrestrial *versus* oceanic sources of battery metals. So far, much of the literature has been focused on simply enumerating the environmental impacts of oceanic or terrestrial mining, whereas we apply industrial ecology principles to consider an evaluative comparison. Environmentalists have campaigned against deep-sea mining and the International Seabed Authority (ISA), which was set up more than three decades ago to regulate oceanic mining on the High Seas. Given the impasse at the ISA, President Trump has issued an executive order to unilaterally move forward with deep sea mining licenses. At this juncture, this paper proposes a timely science-based approach to evaluate options for extraction sites for battery metals.

1 Introduction: extractive context and controversies

The paradigm of industrial ecology assumes that anthropogenic systems of production can mimic or harmonize with natural systems in terms of energy and material flows. On land, such interactions have more opportunities than they do in the oceans since there are numerous nodes of human industrial activity. Thus, it is easier to conceive of phenomena such as industrial symbiosis – a collaborative system in which the underutilized materials, energy, water, or byproducts of one company are used by others to improve overall resource efficiency. Subsequently, eco-industrial parks can host co-located businesses designed to enable industrial symbiosis through collaborative resource and environmental management. However, this is challenging in the oceans, where industrial activity is often more targeted, distant, and disconnected from other human activities. For example, some of the key human industrial activities in the oceans, such as long-distance fishing, shipping, or oil and gas extraction, have limited linkages to most people's homes or communities. Nevertheless, many general concepts of industrial ecology can be adapted to the ocean environment to help manage oceanic resource use, such as seaweed farming, aquaculture, or bio-carbon capture.[1,2]

This paper provides a conceptual basis for considering the application of industrial ecology methods to oceanic mineral

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[a] University of Delaware, Department of Geography and Spatial Sciences, USA. E-mail: saleem@alum.mit.edu

[b] University of New South Wales, School of Mineral and Energy Resource Engineering, Australia

[c] United Nations University, Institute for Water Environment and Health, Canada

[d] Colorado School of Mines, Payne Institute for Public Policy, USA

[e] Choate Rosemary Hall Academy, USA

† Saleem H. Ali and Alexander Gilbert designed the study.

‡ All three authors contributed to the writing of the manuscript.

extraction, which is proposed under the United Nations Convention on the Law of the Sea (1982), also known as UNCLOS. Application of these methods can help address ongoing conflicts on metal supply sourcing in terrestrial contexts while managing input substitution from oceanic deposits. Mining activity, particularly of metals, has key features that make it more suitable for industrial ecological analysis and such an approach can also better inform "adaptive management" of deep sea minerals.[3] First, metal supply chains can lead to a range of products from the construction sector to electronics, which can provide fertile opportunities to find efficiencies across sectors. Second, metals are increasingly being recycled, and the comparisons between primary and secondary supply streams are well-suited for applying industrial ecological techniques. Finally, there has been considerable investment by the international community in tracking and tracing technologies for metal supply chains due to concerns about conflict minerals and metal supply security for the defence establishment.

Although some scholars have opined that comparisons between land and sea mining are incongruent due to unique biodiversity characteristics,[4] an industrial ecological analysis of the oceans requires us to consider an integrated planetary vision which links oceanic and terrestrial activities from an earth systems perspective. For coastal activities, it may be possible to have more tightly coupled direct linkages as well, but this is less possible for open waters and in the deep sea.[5] Thus, coastal sand mining or diamond mining, which has been occurring for decades, has some opportunities for terrestrial linkages with human systems.[6] Coastal sand mining can accelerate erosion or cause other physical disruptions, impacting human recreational uses or natural ecologies.[7] The most meaningful industrial ecological applications regarding deep-sea mining are likely to be in comparing the full life cycle impacts of terrestrial and oceanic mineral reserves in terms of a variety of ecological and social indicators.[8]

Human use of the oceans as a major source of material and energy for the global economy has a long and tortured history going back to the use of whale blubber for lantern oil in the thirteenth century. Offshore oil and gas drilling then commenced in the late nineteenth century and continues to this day in ever deeper waters. During the mid-20th century, technologies opened the use of seabed or sub-seabed solid mineral resources as well, but exploitation has thus far been limited to coastal areas. The main industrial activities in the deep sea are transportation, fishing, and oil and gas drilling. Of these, oil and gas drilling most closely resembles deep sea mining in its relationship with the seabed and potential effects on benthic ecosystems, yet the locations and effects differ significantly from mining. Indeed, oil and gas extraction has additional occupational hazards and disaster potential associated with the flammability of the resource under high pressure.

Commercial interest in deep seabed minerals is driven by growing terrestrial demand for metal commodities. Thus, deep sea mining would be an input to the broader global economy. Metals are foundational commodities for modern goods, especially electronics; the energy transition is contributing to projected growth in metal demand.[9] Many clean energy technologies, like wind, solar, and batteries, rely upon large quantities of metals. Effectively, the energy transition is poised to drive a shift in planetary resource use for energy from biogenic fuel extraction to one built on and constrained by metals.

However, despite the rising and increasing demand for metals, consumption may not cause resource and reserve depletion in the 21st century due to ongoing terrestrial mineral exploration and development of new extraction technologies. Rather than depletion, Jowitt, Mudd, & Thompson[10] suggest that environmental, social, and governance factors are likely to be primary constraints on mineral production and supply. Nevertheless, as the best reserves are targeted first, decreasing resource quality and greater energy requirements could impact relative metal prices, supporting alternative mining sources.[11] Beyond economics, mining can have substantial negative social and environmental impacts through pollution and land use. Mitigating these impacts requires effective resource governance.[12] However, existing practices to identify and manage negative externalities have gaps at the national, supply-chain, and company levels. Klinger (2017) argues that the relegation of rare earth mining to the frontiers of society is as much about imperialism and power through resource extraction as it is about rare earth resource availability.[13] Such an argument could just as well be made about other, more common metals when it comes to interest in the deep sea.

As constraints grow, nations and industry are investigating alternative sources of metal supply. These may come from the global commons, minerals from the deep sea, or from outer space. Deep seabed mining (DSM) is an expansion of the human industrial ecosystem and footprint to areas largely untouched by direct human activities. There are three primary categories of polymetallic DSM sources, though the most dominant metals in these reserves are manganese, cobalt, nickel, and copper:[14]

- Cobalt crusts can provide Co, Te, Mo, Bi, Pt, W, Zr, Nb, Y, and rare-earth elements (REEs)
- Seafloor massive sulfides (SMS) can provide Cd, Ga, Ge, In, As, Sb, and Se
- Nodules are sources of Ni, Cu, Co, Mo, Zr, Li, Y, and REEs

From an economic geology perspective, deep sea minerals are almost exclusively resources – most are inferred and have yet to become proved reserves. Nevertheless, Hein *et al.*[15] estimate that ocean resources may be larger than terrestrial reserves for at least Tl, Mn, Te, Ni, Co, and Y, in some cases by orders of magnitude. Further, many oceanic deposits have higher ore grades than terrestrial deposits.[16]

2 Applying industrial ecology methods to mining

Mineral extraction has been the subject of intense environmental conflicts worldwide as communities are concerned about risks to their health and livelihoods around terrestrial mining sites. The prospect for mineral extraction from the deep sea may reduce conflict with competing land uses and direct risks to human populations. However, the marine environment is a vital ecological zone, and the deep sea remains largely unexplored. Considering the trade-offs is a major challenge for environmental systems scientists who are keen to see the interconnections between various ecologies. In this context, we suggest the application of methods from the field of industrial ecology to comparatively evaluate these trade-offs and provide a cogent means of effective environmental decisions for sourcing critical minerals.

Applying industrial ecology methods to mining can be approached in two ways: (a) local environmental resource usage in the production of the mine's output itself, and (b) systems sustainability implications of differentiated source streams for the mineral, which requires an evaluation of the entire supply chain for the mineral. For the purposes of this paper we will cover both facets of local and systemic industrial ecology in the context of sourcing metals from the oceans. Indeed, the local impacts of the extraction process inevitably gets incorporated into systems-wide calculations.

There is no clear, commonly accepted definition of industrial ecology due to different perspectives and techniques. Generally, however, industrial ecology is described as a field that combines economics and ecology to evaluate micro to macro behaviours in industrial systems based on observations of the behaviour of industrial systems.[17] Nor is the industrial structure of deep-sea mining yet fully defined – while proposals exist in different stages of development, the overall process lifecycle is still to be determined.

Five analytical approaches relevant to applying industrial ecology concepts to ocean systems are discussed below. Four core industrial ecology approaches are summarized in Table 1. Environmental Impact Assessment (EIA) is not listed separately in Table 1, as this omission is deliberate: the table focuses on methods typically considered central to industrial ecology. EIAs are typically project-focused and spatially and temporally bounded, whereas industrial ecology methods emphasize system-wide, comparative, and life-cycle perspectives. Outputs from EIAs, such as baseline environmental data and impact estimates, can nevertheless inform industrial ecology analyses, particularly when integrating local impacts into broader supply-chain and planetary-scale evaluations.

2.1 Design for environment

As a starting point the design of industrial systems to consider ecological factors requires us to go back to key thermodynamic evaluation. The system should have fundamental attributes of mitigating energy and material usage in delivery; mitigate waste generation; and subsequently facilitate reuse and recycling of material inputs towards a circular economy. The extraction systems proposed for oceanic mineral deposits currently have the advantage of waste mitigation due to higher grade ores and processing plants may not require large tailings facilities that are needed for terrestrial metal ores. However, there are different proposed models for processing of oceanic ore, such as oceanic, terrestrial, or hybrid processing designs, which would shape ultimate material flows and waste outcomes. Further, the polymetallic nature of oceanic deposits could lead to greater overall production of metals but may have different energy and other requirements for separation.

2.2 Dematerialization

Infrastructure needed to access mineral deposits in the case of oceanic deposits focuses on large seaborne vessels, underwater remote operated vehicles, and the industrial process between

Table 1 Comparative applications of industrial ecology approaches

Name	Design for environment	Dematerialization	Life cycle analysis	Systems synthesis
Definition	Design for environment is a type of design approach aimed at reducing the negative environmental effects of a product, process, or service	Dematerialization is the process of delivering the same product or service while using fewer total materials	Life cycle analysis is a method for assessing the environmental impacts of a product or service throughout its entire lifetime	System synthesis is the analysis of an industrial or ecological system, considering material, energy, environmental, and social factors to optimize overall performance and sustainability
Real world example	Patagonia's sustainable clothing practices. They focus on using recycled and renewable materials and minimizing the waste in manufacturing. This approach is aimed at limiting their environmental effects	In the 1970s, approximately 22 aluminium beverage cans could be produced from one pound of aluminium. Today, the same quantity of material can produce roughly 32 cans. Expressed as output per unit of material, this dematerialization illustrates a reduction of approximately 38% in the average weight of an aluminium can since the 1970s, while maintaining the same beverage volume	Comparing the environmental impact of electric vehicles to gas powered cars over their life cycle	In electric vehicle production, system synthesis is used to evaluate the entire battery supply chain. Engineers consider environmental impacts, energy use, and social factors at every stage to optimize the system as a whole

extraction and ultimate sale, whether at sea or onshore. This infrastructure needs to be compared in terms of material usage with the roads, railways and energy infrastructure needed when mines are developed on land. There is potential for dematerialization by reducing overall material inputs to metals production by moving extraction and potentially processing to the oceans.

2.3 Life cycle analysis (LCA)

A composite comparison between terrestrial and oceanic extractive industries from mines to markets can most effectively be carried out through an LCA. Much of industrial ecology discourse has developed around a range of LCA methodologies which range from calculating carbon footprints to social cohesion metrics. For oceanic minerals in the deep, the social LCA analysis comes out quite favourably overall since there are no communities to physically displace or property regimes to manage. For coastal oceanic mining the situation may be more comparable to terrestrial mining, especially considering social dimensions. However, there is more limited experience in applying LCA to marine environments compared to terrestrial environments. The field is experiencing ongoing refinement in methodologies and focus for marine contexts but still lack the spatial and temporal precision of common terrestrial approaches and model.

2.4 Systems synthesis

Much of the debate on oceanic minerals is also couched in terms of their use for green technologies such as wind and solar power infrastructure or electric car batteries. The imperative to build such infrastructure comes from concerns about human impacts on the planet's most critical life-sustaining indicators. The time sensitivity of the tipping points in this discourse on planetary boundaries makes the need for the technology development more urgent. Hence the option of waiting for alternative technology development and accumulation of recycled stocks of metals to be available for eventual circularity become less plausible. Recycled stocks accumulation is dependent on product durability whose benefits also need to be measured and compared with the need for more mined inputs through LCA (Fig. 1).

Climate change mitigation, that would be one of the uses of the metals, factors into such analyses as does oceanic ecology and thus the trade-offs of sourcing metals to meet demand need to be considered. Within this context only enough metal to have a sustainable stock for recycling should be extracted, ultimately leading to a circular economy in the sector. The modularity of metal uses in electric car batteries makes such circularity plausible. While recycling metals is an essential part of an industrial ecology approach, its impact is ultimately reliant on recovery rates and collection. At commercial facilities, recovery efficiencies for cobalt and nickel commonly exceed 70–80%. In

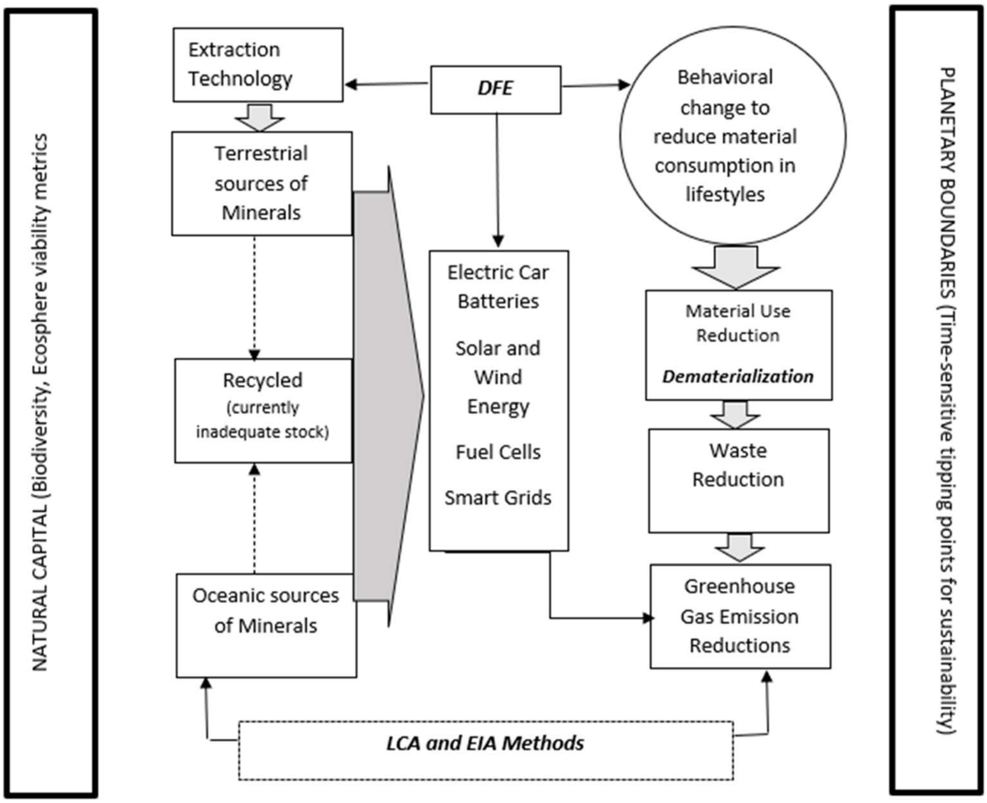

Fig. 1 Applying industrial ecology approaches to evaluating the viability and need of oceanic mineral extraction. The system's approach considers natural capital and key time-sensitive tipping points as the limiting "walled" parameters for decision-making. Industrial ecology methods are italicized.

contrast, lithium's end-to-end recovery remains substantially lower, typically below 50% and, on a global average, likely under 20% when collection losses are included. However, recent research has found improvements in recycling recovery rates. Hydrometallurgical and direct-recycling routes report greater than 90% recovery for cobalt and nickel, and up to 90–93% for lithium, from standard cathode chemistries. The European Union's new battery mandate has set minimum recovery efficiencies at 95% for nickel, cobalt, and copper, and 80% for lithium, by 2031.

3 Oceanic exceptionalism

The argument can be made that ocean systems are qualitatively so different from terrestrial systems that we should not even attempt a comparison. Since there are no human settlements near current proposed deep sea mining sites in the Pacific ocean, comparisons are also made in terms of socioeconomic impacts for terrestrial mining communities of a shift in metal supply sources.[18] Some ecologists have suggested that the only meaningful way to compare land and oceanic mining is to use an "environmental impact wheel" through which a profusion of indicators and attributes are collectively represented.[19] However such an approach can rely on normative choices related to indicator selection, scoring, and weighting, which can influence assessment outcomes and therefore requires careful transparency and safeguards. The industrial ecology approach focuses on clearly measurable attributes rather than conflating those which cannot be measured easily (like biodiversity) with those which can (such as waste generation or carbon footprints). Nevertheless, industrial ecology still has certain subjective aspects such as modelling assumptions, and data selection and similarly require explicit safeguards to ensure appropriate interpretation.[20]

3.1 Local industrial ecology of deep-sea mining

Most existing work on the industrial ecology of deep-sea mining focuses on the project-related environmental impacts of proposed mining activities. This work is foundational for planetary-scale analysis. DSM can impact local ecosystems and environments in remote locations that are largely untouched by humans. Miller *et al.* (2018)[21] describe a generic design for a seabed mining system: a seabed resource collecting system, a lifting system to the ocean surface, and support vessels for processing and transportation. Due to the extreme depths and pressures involved, the seabed collecting systems are most likely to consist of remotely operated vehicles (ROVs). The ROVs collect ore using drills, mechanical removal from seabed, or by collecting polymetallic nodules that are openly on the seafloor. Of these, nodules may be closest to economic extraction; they can be gathered directly by roving ROVs whereas SMS may require multiple ROVs and require undersea intermediary steps.[22] The scale and severity of impacts depend on the mining system and the biological and other environmental characteristics of a mine site. However, any estimates remain subject to substantial uncertainty and controversy.

Of major environmental concerns, the potential impacts on life on the deep seabed are the largest likely impacts, and among the hardest to quantify given data uncertainty. At a high level, the size of the deep-sea environment means it is the largest ecosystem on the planet, with a high amount of expected biodiversity that is often fragile (Ramirez-Llodra *et al.*, 2010). Each type of DSM resource and locations within types have distinct endemic species, subspecies, and populations. The abyssal plains, the locations of polymetallic nodules, are home to megafauna, macrofauna, meiofauna, and bacteria that live on the seafloor or in the top layer of sediment, surviving on nutrients falling from the surface. Cobalt crusts host sessile epifauna (such as corals and sponges) dependent on the seabed surface and existing in ecosystems that may already face some pressures due to deep sea fishing. Unique even among this biodiversity, SMS deposits near active hydrothermal vents are hosts to chemosynthetic life which feed off of chemical releases and support specialized, local ecosystems.[23] These ecosystems may be particularly vulnerable to deep sea mining as direct and indirect damages to vents and ecological communities could have long-term biological effects.[24] Notably, mining plans for SMS deposits focus on inactive vents, which have less biodiversity than active vents but may be located near active vents and host endemic species.

Benthic fauna and pelagic fauna are linked ecologically meaning that direct DSM impacts on the seafloor and sediment plumes could impact pelagic species and hence plume analysis could be compared with disruption to hydrological systems on land. While recovery by some species is possible, direct damages from ROV mining operations and indirect impacts on broader biodiversity can ultimately lead to community shifts on long-term timescales. Data from an experimental mining track showed that 26 years after mining nematode assemblages suffered decreases in diversity and density in disturbed areas with similar long-term losses of microbial populations. The same study found that while the marks of a mining experiment from four decades ago are still prominent, some mobile fauna have shown signs of recolonization, with density roughly approaching reference site levels.[25]

The goal of "no net loss" is impossible to objectify at the level of each nodule. Polymetallic nodules take millions of years to form, making their removal a permanent act of damage. Additionally, the high degree of uncertainty regarding deep-sea biodiversity makes it nearly impossible to quantify what would be lost or gained. Beyond impacts on individuals and populations, DSM activities can also impact ecosystem functions and potentially degrade ecosystem services. As with deep sea biology, there is limited understanding of deep-sea ecosystem services. Armstrong *et al.* (2012)[26] provided an early attempt to bridge this gap, finding that an ecosystem service framework can identify multiple benefits from deep sea ecosystems and environments. These include:

- Supporting services such as habitats, nutrient cycling, and genetic diversity
- Provisioning services of food stocks
- Regulating services especially of toxics and greenhouse gas sequestration

- Cultural services.

Environmental management techniques form the basis for industrial and policy mechanisms to address biological and ecosystem concerns with DSM. Environmental impact analyses (EIAs) or environmental impact statements (EISs) that are widely used for terrestrial mining can be adapted to deep sea activities to identify prospective risks.[27] However, the effectiveness of EIAs for the deep sea can be limited by scientific uncertainty, poor methodologies, no baseline data, limited details on mining techniques, and insufficient risk analysis. General frameworks for mining activities provide a blueprint to limit biodiversity loss through avoidance, minimization, remediation, and offsets.[28]

3.2 Industrial ecology and economics of deep-sea mining

Due in part to a lack of existing deep sea mining activities, relatively little scholarly work has examined how deep-sea mining will interact with broader planetary-scale efforts to meet mineral demands. Despite local-level analyses of both terrestrial and ocean mining, a lack of integrated analysis limits the ability to fully compare the net effect of ocean mining on terrestrial mining activities. The material function of ocean mining within the global mineral supply system is identical to that of terrestrial mines – it is an initial input into the supply chain and mineral cycle. However, the geological characteristics of deep-sea mineral deposits impose important constraints on how these resources can be assessed and compared.

As the foundation of the modern global economy, the cradle-to-grave supply chain of metals has large negative environmental and social impacts. Terrestrial mining is globally distributed based on identified resource ores, inputs costs, and regulatory environments. Mines can be both dedicated to specific minerals or produce multiple minerals.

Oceanic mining is qualitatively different in most measures from terrestrial mining. Due to the remote location of mining activities, it does not have resident communities. Hence it may lack direct social impacts and may not pose substantial indirect social impacts. Indeed, Wakefield and Myers (2018) found net social benefits from DSM for Papua New Guinea and the Cook Islands due to the economic benefits without clear social costs.[29] However, there may be social impacts that are yet to be fully identified, including social effects from impacts on fisheries and reduced value of coral reefs. To the degree there is civil societal concern about deep sea mining, it will not necessarily be driven by concerns about land displacement and local pollution. Rather it will be shaped by concerns about regional environmental pollution, effects on fishing and other aquatic life, displacement from marine spatial planning, and, to a lesser degree, aesthetic and cultural values. One study suggested the perception of damages from DSM could negatively impact the economy of Fiji by reducing tourism revenue from scuba divers.[30] Although not yet incorporating DSM, planetary boundary frameworks are now considering the effects of oceans and resources; to the extent that DSM can contribute to reducing planetary burdens it could expand planetary boundaries.

Mullins and Burns (2018)[31] discuss the fiscal dimensions of DSM, focusing on Pacific Island States, where limited revenue bases raise the importance for efficient resource governance. High capital intensity, technological uncertainty, and extended development timeframes are characteristic features of DSM projects, under which conditions public revenue generation is complex. The analysis indicates that corporate income tax will be unlikely to provide any meaningful government revenues in the initial years of mining. Instead, they emphasize how Ad valorem royalties, set in the range of roughly 3–7% of mineral value, can offer predictable revenues from the commencement of production, while profit-based instruments like corporate income tax and resource rent taxes allow states to capture economic rents once projects achieve higher levels of profitability. Exclusive reliance on profit-based taxation cannot work in the DSM context because profitability may be delayed and base erosion *via* transfer pricing is a risk. Fiscal regimes in the early stages of development for the Cook Islands and Tonga reveal how fiscal design will determine whether DSM becomes a source of public revenue or reproduces extractive economic asymmetries.

Beyond environmental impacts, industrial ecology also requires attention to how economic and institutional structures shape system outcomes. Deep sea mining (DSM) has the potential to generate substantial revenues for Pacific Island countries, but data shows that outcomes depend more on revenue governance than on income scale alone. Previous experience with extractive industries demonstrates that poorly managed resource revenues can lead to economic instability and long-term decline; for example, phosphate mining in Nauru produced a GDP peak of approximately US$178 million in 1973, before collapsing to under US$19 million by 2007 following prolonged mismanagement. To avoid similar outcomes, studies emphasize the need to integrate DSM revenues into transparent fiscal frameworks featuring public reporting, independent audits, and oversight by ministries of finance rather than sector-specific agencies. The establishment of sovereign wealth funds is frequently recommended, with global experience showing such funds collectively manage an estimated US$3–5 trillion in assets, highlighting their capacity to stabilize volatile resource income, mitigate risks such as inflation and Dutch disease, and promote intergenerational equity in the use of non-renewable marine resources.[32]

The different characteristics of terrestrial and oceanic mining make direct comparisons hard, underlying the lack of panoramic analysis. Both types of mining can negatively damage the local environment and biodiversity. Deep sea mining is characterized by difficulties and uncertainties related to biodiversity surveys, environmental monitoring, establishment of baselines, and incomplete understanding of broader ecosystem interactions. These factors are driven primarily by the technological challenges of accessing the deep seabed whereas terrestrial mining usually suffers them through a lack of national capability or sufficient governance. Critically, differences between terrestrial and marine life in both environments makes biodiversity comparisons hard.

Nevertheless, some factors can be compared. Paulikas *et al.* (2020)[33] conducted a life cycle climate change quantification of producing batteries with minerals from terrestrial ores *versus* deep-sea nodules. They found that nodules reduced greenhouse gas emissions by 4–55% due to lower energy intensity of extraction and processing and even further by avoiding land use from mining operations that reduce carbon sequestration. They also hypothesize that nodules could have greater environmental benefits by displacing marginal terrestrial mines – new and high-cost projects with the greatest potential to cause new degradation. Importantly, while overall life-cycle emissions may be lower, the energy demand for the mining stage of DSM is higher than that of onshore mining due to the technical challenges of offshore extraction. Comparably an early LCA study of DSM impacts indicated that energy demand for the mining stage of DSM could be significantly higher than onshore deposits; the benefits largely accrue through reduced processing energy related to the high ore grades of targeted ocean deposits.

Studies commissioned by Nautilus as part of its proposed Solwara 1 deep sea mine in Papua New Guinea evaluated the economics, systems design, and environmental impacts of the project, particularly compared to other copper mining activities[34,35] Comparably, Barker and Schmidt (2015)[36] found that Solwara 1 had less damages on provisioning services, regulating services, supporting services, and cultural services. A Pre-Feasibility Report on the economic viability of its NORI-D Project, located within the CCZ. The study estimates the operation's after-tax net present value (NPV) at $5.5 billion. It also projects an Internal Rate of Return (IRR) of 27%, demonstrating economic growth. The study also highlights the economic costs, displaying an All-In Sustaining Cost (AISC) of $2569 per tonne of nickel. Overall, it estimates that over the 18 year lifespan of the NORI-D Project, total operating expenditure will be roughly $39.9 billion to produce 12 million wet tonnes per year.

While company-sponsored pre-feasibility studies provide useful insight into proposed project economics, they are inherently subject to uncertainty and commercial incentives. External market-oriented critiques, including analyses by Iceberg Research, have raised concerns regarding assumptions used in such studies, including discount rates, cost benchmarks, and recovery estimates.[37] However, these critiques as with the industry reports are not peer reviewed and often rely on selective assumptions, non-equivalent comparisons, or qualitative governance considerations rather than transparent sensitivity or scenario-based economic analysis.[38] Further peer-reviewed research that links industrial ecology to economics from a systems-oriented perspective with a range of scenarios is needed to better inform decision-makers in this regard.

4 Global governance of deep-sea mining

The nature of industrial activities and their operational constraints globally are defined by the legal context in which they occur. The utilization and application of industrial ecology principles depend on the legal framework. Ocean mining differs significantly from terrestrial mining due to a different regime under international and national laws. Every part of the Earth's surface other than Antarctica is subject to the territorial sovereignty of a nation-state (or competing claims by two or more nation-states). Under this model, nations can generally conduct mining operations as they see fit, so long as it does not interfere with other nations. Environmental pollution, social opposition, and the ability to access markets ultimately pose the primary constraints on how national decision-making impacts terrestrial mining flows. Comparably, the customary law of the sea and the statutory United Nations Convention on the Law of the Sea (UNCLOS; 1982) create a tiered and overlapping system of national sovereignty and international commons for ocean resources. The major types of oceanic territory and governing regime are presented in Table 2.

For purposes of deep-sea minerals, this system creates two primary regimes: national governance of minerals in territorial waters, EEZs, and continental shelves, and international governance of minerals located in the "Area" underneath the High Seas. The area is governed under the principle of "common heritage of mankind." Notably, many coastal nations lack the means to enforce national restrictions on fishing in their EEZs and even in territorial waters. The ISA is potentially

Table 2 Governance of global oceans

Area	Distance from land (nautical miles)	Governing rules
Terrestrial territory	0	Complete national sovereignty
Territorial waters	0–12	Complete national sovereignty
Contiguous zone	12–24	International waters, nations can claim for purposes of enforcement related to territorial waters
Exclusive Economic Zone (EEZ)	12–200	International waters but national sovereign rights over seabed and fishing activities
Continental shelf	Up to 350 can be claimed if part of continental shelf	International waters but national sovereign rights over seabed
High Seas	All parts of the sea beyond territorial waters and EEZs	International waters – many rights, limited obligations
The "Area"	Seabed of the High Seas	"Common heritage of mankind" – managed by the international community

committed to establishing mechanisms for enforcement of its regulations through inspectors on the extraction vessels themselves.

4.1 National environmental management

In territorial waters, EEZs, and claimed continental shelves national governments have jurisdiction over deep seabed minerals and thus are responsible for governing their extraction and associated environmental management. However, there has been an attempt by the United States to also use national laws to engage with international waters. The United States using the Glomar Explorer conducted initial deep seabed surveying of polymetallic nodules before the development of UNCLOS. There has been during treaty negotiations, the US passed a domestic policy framework with the Deep Seabed Hard Mineral Resources Act (DSHMRA) that allowed license entities to extract minerals from the seabed of the High Seas. Importantly, this act included exploration and exploitation licensing under the National Environmental Policy Act (NEPA) framework, the foundational environmental disclosure of the US. Under NEPA, federal agencies must publish a statement about the environmental impacts of major federal actions significantly affecting the quality of the human environment. DSHMRA provided specific implementation guidelines for NEPA that included a programmatic analysis to inform a licensing regime.

4.2 Governance and environmental management of the area

UNCLOS was adopted by the international community, with the United States declining to ratify the treaty. As a result, the United States is excluded from sponsoring mining activities in the Area and is limited to deep-sea mining within areas of national jurisdiction. However, the United States under President Trump has initiated a unilateralist approach with respect to deep-sea mining activities in international waters. An executive order issued in April 2025 is now allowing for permitting of projects through the National Oceanic and Atomospheric Administration (NOAA).[39] The industrial ecology approach could also be utilized in this context. The potential regional impacts of deep-sea mining within adjacent areas of national jurisdiction could further benefit from information-sharing, coordination, and perhaps regional governance.

When it comes to governance of the Area (the seabed underneath the High Seas), the UN Convention on Law of the Sea has created the International Seabed Authority (ISA). The ISA is tasked with managing mining activities in the Area. It is mandated with issuing licenses for mineral exploration and exploitation while also ensuring that such activities are consistent with protection of the marine environment under UNCLOS Article 145.[40] The governance structure of the area has significant implications for its utilization and its impact on overall mineral flows. During negotiations on UNCLOS, there were brief discussions on imposing production caps, ostensibly to protect the mineral exports of emerging economies. While this cap was ultimately dropped during negotiations, the governance structure of the ISA gives substantial power to countries that are heavily dependent on their terrestrial resource base, as well as those that lack a resource base. UNCLOS also includes a profit-sharing mechanism designed to benefit emerging economies, part of the treaty's promise of treating the Area as the “common heritage of mankind.”

Empirical assessments of polymetallic nodule resources suggest that deep-seabed mining could exert a non-trivial influence on global metal supply, particularly for manganese, nickel, copper, and cobalt. A detailed techno-economic analysis of the Indian Ocean Nodule Field (IONF) estimates that India's retained exploration area of approximately 75 000 km^2 alone contains roughly 365 million metric tons of dry nodules, comprising an estimated 49 MMT of manganese, 2.2 MMT of nickel, 2.1 MMT of copper, and 0.2 MMT of cobalt, with an aggregate *in situ* metal value of approximately US $158 billion. Modelling 25 year period indicate that such operations could achieve internal rates of return exceeding 12% under conservative price assumptions, while supplying up to 80% of India's nickel demand and producing over 3000 tons of cobalt annually.[41]

An independent 2018 review of the ISA's operations against other international resource governance bodies found it to have significant deficits in transparency. The same study applied a standardized framework of 30 transparency indicators, through which the ISA scored an overall 44%, compared to the average score of 77% achieved by regional fisheries management organizations operating in similarly internationalized spaces. The study found performance was particularly weak on access to data and decision-making, and that none of the environmental and safety data received from deep-sea mining contractors had been published despite UNCLOS provisions establishing that such information shall not be considered confidential. In addition, the ISA's central data repository contained no data from contractors, and it relied mostly on historical scientific cruise records; as in 2018, the most recent dataset pertained to 1998, further limiting the ability of independent environmental assessment. Restricted access to key bodies like the Legal and Technical Commission and the confidentiality of exploration contracts further constrain external scrutiny and raise serious questions about accountability as the ISA moves toward developing regulations to license commercial deep-sea mining activities.[42]

Legal analyses of the “common heritage of mankind” principle emphasise that it is intended to operate as a substantive constraint on deep-seabed exploitation rather than a purely procedural designation. In this interpretation, the International Seabed Authority is expected to act as a trustee of a global commons, with obligations extending to intergenerational equity and the preservation of ecological integrity. However, assessments of emerging ISA rules suggest that these obligations remain weakly operationalized, with benefit sharing and environmental safeguards frequently deferred or left indeterminate. This raises concerns that the common heritage principle risks functioning more as a legitimising narrative for extraction than as an effective mechanism limiting extraction intensity or cumulative environmental loss.[43]

Together, these structural incentives will shape the degree to which oceanic mining may be selected over terrestrial mining. This is a unique regime that empowers the international community in controlling mineral flows compared to terrestrial mining, which is under the exclusive national jurisdiction of individual countries. Comparably, the two other global commons which may provide material resources, Antarctica and outer space, do not have international governance of resource production.

In addition to mineral governance, the ISA is also responsible for operationalizing environmental management for DSM activities in the area.[44] It has developed regulations for overseeing baseline monitoring during the exploration phase, including the requirements for environmental impact analysis for new projects.[45] Chief among its activities, ISA has developed a Regional Environmental Management Plan (REMP) for the Clarion-Clipperton Zone which has many nodule resources.[46]

However, ISA has yet to develop comprehensive requirements for the exploitation phase of mining, with substantial gaps related to establishing environmental goals and objectives suggest that the ISA needs to develop a clear Strategic Environmental Management Plan. Beyond proactive environmental management, other potential gaps remain including clearly defining liability and enforcement.[47] Terrestrial deposits can face significant restrictions from environmental concerns, tied to local pollution and population opposition. Without an effective management system, a lack of environmental protections could lead to a large shift from terrestrial to oceanic mining.

5 Conclusion: towards planetary mineral governance

Deep seabed mining can contribute to meeting future mineral needs and reduce the need for additional terrestrial mines, but this is only possible with coordinated governance mechanisms to prevent rampant extractivism. The idea of a Minerals Trust for the green transition could allow for a focused effort to ensure any deep-sea extraction is offset by reduction in terrestrial extraction.[48] Battery technologies could be a focal point for such a trust mechanism as the metal supply and source are easy to track as well. Increasing demand for metals from economic growth, population growth, and the energy transition underlie emerging commercial interest in deep sea minerals. However, each of the three major types of deep-sea resources exist in unique, remote, and unknown environments. Biological resources and diversity are likely the primary constraints on any DSM activities.

An industrial ecology perspective on DSM can provide perspective on how to integrate deep sea mineral supplies, identify impacts, and guide mitigation. At a systems level, DSM is primarily about input substitution, replacing terrestrial mineral sources with oceanic sources. The high ore grades of deep-sea minerals could reduce processing and other front-end costs. Further, as metals often feature significant amounts of co-production and byproducts, the specific coupling of mineral products in deep sea deposits could cause large scale reorganization of market dynamics. DSM achieves this input substitution and potential altering of mineral coproducts by expanding the human industrial footprint offshore and into areas previously untouched by direct human activities. Future research can examine the complexity of this input substitution and how market dynamics may be shaped by changing product in-flows.

Critically, the extent of environmental management of mining activities will be determined by the legal framework. National governments are beginning to address these issues, as is the International Seabed Authority. Location-specific impacts can be difficult to compare across regions, especially so for comparisons between terrestrial and oceanic mining. Frameworks at the individual level can focus on minimizing uncertainties, monitoring impacts, and mitigating damages. Nevertheless, limitations in environmental management tools related to scientific and technical uncertainty undermine the near-term ability to understand and mitigate DSM risks. Globally, systems need to balance amongst many competing environmental, social, and economic forces. There is a danger that the out-of-sight out-of-mind nature of deep-sea mineral resources could lead to their overexploitation relative to terrestrial deposits. Ultimately, there is a need for a framework for industrial ecology decision making on planetary metals.

At the international level, there is an opportunity for industrial ecology approaches to assist with decision-making on specific aspects of natural resource governance. For oceanic governance, the new international agreement on Biodiversity Beyond National Jurisdictions (BBNJ) under the U.N. Law of the Sea Convention which came into force in January 2026 could have important ramifications for deep sea mining as there are provisions to create protected areas in two thirds of the ocean beyond national jurisdictions.[49] Industrial ecology metrics could be useful in the implementation of key aspects of this treaty and how it may come into conflict with the ISA's regulations and provisions to allow for deep sea mining. Decision-making on deep sea mining must be calibrated carefully with risk-reward trade-offs that in turn need to be updated as we learn more about the ecosystems where extraction is to occur.

Conflicts of interest

There are no conflicts of interest to declare.

Data availability

This paper is conceptual in nature and does not involve specific empirical data. However, the articles cited all have publicly available information.

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