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Authors
Levin, Lisa A
Amon, Diva J
Lily, Hannah

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Challenges to the sustainability of deep-seabed mining

Lisa A. Levin[1] ✉, Diva J. Amon[2] ✉ and Hannah Lily[3] ✉

This Review focuses on whether the emerging industry of deep-seabed mining aligns with the sustainable development agenda. We cover motivations for deep-seabed mining, including to source metals for technology that assists with decarbonization, as well as governance issues surrounding the extraction of minerals. Questions of sustainability and ethics, including environmental, legal, social and rights-based challenges, are considered. Slowing the transition from exploration to exploitation and promoting a circular economy may have regulatory, technological and environmental benefits.

The deep-sea floor (below 200 m) is presently, along with Antarctica, the only area on Earth where mineral resources are not currently extracted commercially[1]. However, the twenty-first century has seen rising concerns over the depletion of the most readily available and highest-grade ores of selected minerals on land, as well as increasing vulnerabilities to political control over resource access[2–4]. Demand for some minerals is also projected to increase, particularly from electrification of the transport sector and renewable energy generation[5–8]. A recent Intergovernmental Panel on Climate Change (IPCC) report indicates that 70–85% of all electricity would need to come from renewable sources by 2050 to limit global warming to 1.5 °C[9]. These factors, combined with the development of a governance structure for international mineral resources established under the United Nations Convention on the Law of the Sea (UNCLOS) and its 1994 Implementing Agreement, have led to renewed interest in deep-seabed mining[4,10].

Many metals occur together at economically interesting concentrations in the deep ocean. These include copper, cobalt, nickel, zinc, silver and gold, as well as lithium and rare-earth elements (Table 1). The metals are found in different ore types in different settings (Fig. 1):

- Polymetallic nodules on abyssal plains (covering 38 million km^2 at water depths of 3,000–6,500 m; 19% of the known nodules are in Exclusive Economic Zones (EEZs)).
- Cobalt-rich ferromanganese crusts which occur between 800–2,500 m on seamounts (occupying 1.7 million km^2 ; 54% of the known crusts are in EEZs).
- Polymetallic sulfides formed at hydrothermal vents near mid-ocean ridges and back-arc basins (covering 3.2 million km^2; 42% of the known sulfides are in EEZs)[11–14].

Relative to land-based reserves, the Clarion-Clipperton Zone (CCZ) alone contains 3.4–5 times more cobalt, 1.8–3 times more nickel, 1.2 times more manganese; and 20–30% of the copper and lithium and 88% of the silver (Table 1). An equal amount of cobalt in the CCZ is present on seamounts in the Pacific Prime Crust Zone (Table 1). A recent report commissioned by a deep-seabed mining company with two exploration contracts in the CCZ suggests that extracting half of the CCZ nodules would provide the manganese, nickel, cobalt and copper needed to electrify one billion cars, while releasing only 30% of the greenhouse gases of land mining[15]. Most of the 300 known marine massive sulfide deposits, potentially valued for copper, zinc, gold and silver precipitated at hydrothermal vents, are smaller in area and less densely clustered in the ocean than on land. Without discovery of new large, off-axis deposits, metals within massive sulfide deposits in the deep sea are unlikely to exceed those of land-based reserves[16] (Table 1). Lithium occurs in seawater, brines and in some minerals, while rare-earth elements may be relatively abundant in deep-sea muds, for example in the North Pacific Ocean[17], but will not be discussed further as there are currently no deep-sea extraction plans being seriously considered.

Mining of the deep seabed has yet to take place, but it is expected to occur via either modified dredging (for nodules) or cutting (for massive sulfides and crusts), and transport of the material as a slurry in a riser or basket system to a surface support vessel (Fig. 1). The mineral-bearing material will undergo minimal processing on board the ship (with wastewater and sediment being returned to the ocean) and be transferred to a barge for transport to shore where it will be further processed to extract the target metals[18]. Compared to terrestrial mining, there is less overburden to remove and no permanent mining infrastructure required[19]. However, in addition to the wastewater and sediment returned to the ocean, there is likely to be solid waste material left after the ore is processed, and disposal mechanisms for this waste could be comparable to those used for terrestrial mine tailings. Although deep-seabed mining is presented here as one endeavour, it is important to note that each resource type (crusts, nodules and sulfides) would have unique environmental challenges, scales, costs and benefits.

UNCLOS gives rights to and imposes duties upon nation states and competent international organizations in different jurisdictional areas (Box 1). In areas beyond national jurisdiction, the International Seabed Authority (ISA) holds regulatory responsibility for both mineral activities on the seafloor (the Area), and the protection of the marine environment from the impacts of those activities. UNCLOS deems the mineral resources in the Area to be ‘the common heritage of mankind’ and charges the ISA to manage seabed mineral activities for the benefit of mankind as a whole, with particular consideration for the interests and needs of developing countries. Since 2001, 30 exploration contracts have been approved

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[1]Center for Marine Biodiversity and Conservation and Integrative Oceanography Division, Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, USA. [2]Department of Life Sciences, Natural History Museum, London, UK. [3]Independent Consultant, London, UK.
✉e-mail: llevin@ucsd.edu; divaamon@gmail.com; hannahlilylaw@outlook.com

Table 1 | Major uses, production and potential supply in selected seabed deposits relative to land-based reserves for metals targeted for deep-seabed mining

Metal	Uses	Deep-sea sources	Annual production in 2017 ($\times10^3$ t)[a]	Annual projected demand in 2050 ($\times10^3$ t) from low carbon energy technology	Metal supply in the Clarion-Clipperton Zone ($\times10^3$ t). The percentage of land-based reserves is given in parentheses[b]	Metal supply in the Prime Crust Zone ($\times10^3$ t)[c]. The percentage of land-based reserves is given in parentheses[b]	Inferred metal supply in seafloor massive sulfides ($\times10^3$ t)[d]. The percentage of land-based reserves is given in parentheses[b]
Copper (Cu)	Used in electricity production and distribution—wires, telecommunication cables, circuit boards. Non-corrosive Cu–Ni alloys are used as ship hulls.	Polymetallic sulfides at hydrothermal vents; polymetallic nodules on abyssal plains.	19,700 (Chile, Peru, USA)	1,378	226,000[e] (23–30%)	7,400 (0.7%)	21,600 (2%)
Cobalt (Co)	Used to produce high-temperature super alloys (for example, for aircraft gas turbo-engines, rechargeable lithium-ion batteries).	Cobalt-rich crusts on seamounts; polymetallic nodules on abyssal plains.	110 (DRC, Australia, China)	644	44,000 (340–600%)	50,000 (380%)	N/A
Zinc (Zn)	Used to galvanize steel or iron to prevent rusting, in the production of brass and bronze, paint, dietary supplements.	Polymetallic sulfides at hydrothermal vents.	12,800 (China, Peru, Australia)	N/A	N/A	N/A	47,400 (21%)
Manganese (Mn)	Used in construction for sulfur fixing, deoxidizing, alloying properties.	Cobalt-rich crusts on seamounts; polymetallic nodules on abyssal plains.	16,000 (China, Australia, South Africa)	694	5,922,000 (114%)	1,714,000 (33%)	N/A
Silver (Ag)	Used in mobile phones, personal computers, batteries. Also used in mirrors, jewellery, cutlery and for antibiotic properties.	Polymetallic sulfides at hydrothermal vents.	25 (Peru, China, Mexico)	15	N/A	N/A	69 (4.3%)
Gold (Au)	Used in jewellery and electrical products (metal–gold alloys).	Polymetallic sulfides at hydrothermal vents.	2.5–3 (China, Australia, USA)	N/A	N/A	N/A	1.02 (0.002%)
Lithium (Li)	High performance alloys for aircraft; electrical, optical, magnetic and catalytic applications for hybrid and electric cars.	Cobalt-rich crusts on seamounts; marine sediments.	43 (Chile, Australia, China)	415	2,800 (25%)	20	N/A
Nickel (Ni)	Stainless steel (automobiles, construction), weapons and armour.	Cobalt-rich crusts on seamounts; polymetallic nodules on abyssal plains.	2,100 (Russia, Indonesia, Canada)	2,268	270,000[e] (180–340%)	32,000 (21%)	N/A

Data included in the table were compiled from refs. [5,12,13,16,86,93]. [a]The top three land producers are shown in parentheses. [b]Note that the land-based reserves are known with enough certainty that they can be mined economically whereas the seafloor estimates are far from this level of certainty. [c]Based on 7,533,000 thousand metric tons in the Prime Crust Zone. [d]Based on 600,000 thousand metric tons in the neovolcanic zone with grades determined as averages of analysis of surface samples. [e]India's 75,000 km^2 nodule claim in the Indian Ocean contains another 7,000 thousand metric tons of Cu and Ni. DRC, Democratic Republic of Congo. N/A, not available.

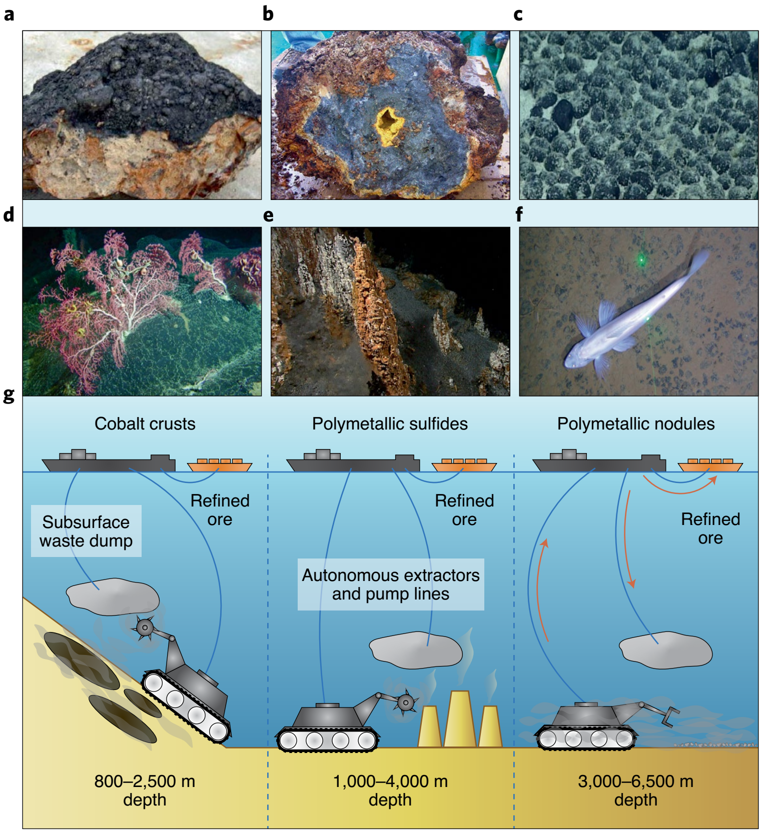


Fig. 1 | Examples of primary mineral resources, associated habitats and extraction mode schematic. a–f, Images of primary mineral resources (**a**–**c**) and associated habitats (**d**–**f**) targeted for deep-seabed minerals mining in international waters. **g**, Schematic of extraction mode. Shown are examples of cobalt-rich crusts on seamounts (**a**,**d**,**g** (left)); polymetallic sulfides at hydrothermal vents (**b**,**e**,**g** (middle)); and polymetallic nodules on abyssal plains (**c**,**f**,**g** (right)). Credit: Evelyn Mervine / SPC[94] (**a**); James Hein, USGS (**b**); NOAA Office of Ocean Exploration and Research (OER; **c**–**e**); Diva Amon and Craig Smith, University of Hawaii (**f**); schematic in **g** adapted from ref. [86], Oxford Univ.

by the ISA. These were granted initially for 15 years each, and those whose terms expired have been extended for five years. Sixteen of the ISA contracts are for polymetallic nodules in the CCZ and two are for nodules elsewhere; twelve others are for crusts and polymetallic sulfides, and occur on West Pacific seamounts in the Prime Crust Zone, the Mid-Atlantic and Southwest Indian Ridges, the Rio Grande Rise off Brazil, and in the Central Indian Ocean (Fig. 2). The exploration contract areas, which in total currently cover more than 1.3 million km^2, are granted to individual states, consortia of states, state-owned enterprises, or companies working with states.

Licenses for deep-seabed mineral exploitation within national jurisdictions were granted by Papua New Guinea (to Nautilus Minerals) and by Sudan/Saudi Arabia (Diamond Fields International)[12,13], though neither site has been mined. Additionally, New Zealand, Tonga, Japan, Fiji, Solomon Islands and Vanuatu have permitted research to assess the mining viability or issued exploration permits for national seafloor polymetallic sulfides, although some of these permits have lapsed. Exploration is planned for polymetallic nodules in the Cook Islands (https://go.nature.com/2UaAx9Z), and cobalt crusts and polymetallic nodules in Brazil[20].

Environmental vulnerabilities

Of the many challenges associated with deep-seabed mining, environmental unknowns, vulnerabilities and costs appear to be among the greatest[21]. The remoteness of most of the deep ocean combined with the harsh operating conditions (high pressure, low temperatures, and darkness) requiring expensive and highly technical equipment, have resulted in limited exploration and scientific research until recently. These constraints, and the vastness of the areas in question, mean that the majority of the deep ocean, both within and beyond national jurisdictions, are poorly characterized and understood, or still completely unexplored[22].

Cobalt-rich crusts on seamounts are the least explored of all three habitat types targeted for mining, and hence their biodiversity has not yet been well characterized[23]. In polymetallic-nodule zones, thought to be bereft of life only 40–50 years ago when UNCLOS was crafted, four decades of research by contractors and scientific organizations show that environments in the CCZ and associated biodiversity are highly diverse but remain largely undiscovered or unidentified. For example, in the eastern CCZ, over 50% of species over 2 cm in size collected by Amon et al.[24] and 34 of 36 species of xenophyophores (single-celled organisms 0.5 to 5 cm in size) collected by Gooday et al.[25] in 2013 and 2015 were new to science. Active hydrothermal vents are the most characterized and understood of the targeted habitats, but many species appear to be rare (comprising <5% of the total abundance in samples), and biological traits and life histories are poorly known[26]. Additionally, biodiversity is rarely studied at and around inactive vents, as well as in areas surrounding discrete, active vents[27].

Finally, the connections of these habitats to the wider global functioning is poorly understood, although new studies of in situ carbon fixation on abyssal plains[28] and hydrothermal vent contributions to surface productivity[29] have begun shedding light on these connections.

Deep-seabed mining is expected to create environmental impacts that involve (1) direct removal of the resources (nodules, crusts and sulfides) which act as substrate for unique fauna,

Box 1 | Legal regime for mineral rights

UNCLOS divides ocean space into zones measured by reference to a baseline constructed from points on the coast of the state.

National jurisdiction:

- The 'Exclusive Economic Zone' (EEZ) is the waters extending to 200 nautical miles (nm) from the baseline (subject to negotiation of boundaries where neighbouring states' EEZ entitlements overlap).
- The seabed and subsoil up to 200 nm is the 'continental shelf' which may extend beyond 200 nm up to 350 nm or further, where specific geological criteria set out in UNCLOS are met.

UNCLOS confers exclusive rights upon all 154 coastal states to engage in the exploration, exploitation, conservation and management of the minerals within their national jurisdictions. UNCLOS (Article 192) also creates a general obligation for states and the International Seabed Authority (ISA) to protect the entire marine environment, both within and outside areas of national jurisdiction.

International jurisdiction:
UNCLOS also establishes two zones beyond national jurisdiction:

- The 'high seas' (the water column beyond the EEZ) (61% of the ocean).
- 'The Area' (the seabed beyond national jurisdiction) (about 50% of the seabed).

UNCLOS declares the seabed minerals of the Area to be 'the common heritage of mankind'. An autonomous intergovernmental body, the ISA, was established by UNCLOS to regulate seabed mineral activities (prospecting, exploration and exploitation) in the Area, which must be carried out for the benefit of mankind as a whole.

which will be removed or crushed. There will also be (2) changes to the geochemical and physical properties of the seafloor; (3) sediment plumes created from the disturbance on the seafloor as well as from the return water that may cloud the water column or smother unmined seafloor areas; (4) contaminant release and changes to water properties; and (5) increases in sound, vibration and light[11,30–33]. The absence of disturbance studies on realistically large scales in space and time means that the intensity, duration and consequences of the impacts of commercial mining remain unknown. Regulators can set rules designed to minimize environmental impacts. However, with limited information available about species-specific responses to impacts and consequences for ecosystem-level functioning, it is difficult to set relevant thresholds to avoid significant adverse change.

Deep-seabed mining also poses a potential risk for biodiversity loss, forced species migrations, and loss of connectivity that could lead to species extinctions in the deep ocean[34]. This places at risk genetic material that could potentially have biotechnical or pharmaceutical use in the future. There could also be impacts to ecosystem services such as fisheries, climate regulation, detoxification and nutrient cycling whose values in the high seas and deep ocean are not yet fully understood or quantified[35].

Understanding biodiversity loss will require much greater baseline knowledge of the communities vulnerable to deep-seabed mining than is held currently[34–36]. As many of the fauna inhabiting vents, nodule-rich abyssal plains and (potentially) encrusted seamounts rely on the resources to be extracted as substrate, local extinctions are possible[31]. For example, Amon et al.[24] observed that half of the species over 2 cm in size in the eastern CCZ relied on the nodules as an attachment surface. If mining was to go ahead with the current state of knowledge, species and functions could be lost before they are known and understood.

Biological communities affected by deep-seabed mining are expected to recover their structure and function slowly following mining disturbance, based on information gleaned from small-scale experiments, as well as from other industries such as seabed trawling. In nodule areas, reduced faunal biodiversity and altered species composition remain two decades after simulated mining disturbance[31,37–40]. Extrapolating to the CCZ, the impacts of polymetallic-nodule mining (taking into account the area directly impacted, as well as the plume deposition area) would be extensive and could lead to an irreversible loss of some ecosystem functions[40], with a soft-sediment community in the interim and full-scale recovery occurring only on the timescale over which nodules form (millions of years). Slow growth (one to a few mm per year) and great longevity (decades to thousands of years) make suspension feeders like cold-water corals and sponges on seamounts highly susceptible to physical disturbance from mining; recovery from substrate removal for organisms dependent on polymetallic crusts on seamounts could require thousands to millions of years, given the rate of formation of crusts[30]. At hydrothermal vents, distinct global faunal patterns, vent site distances and natural background disturbance regimes make it currently impossible to predict recovery rates using volcanic eruptions in other regions as an analogy for deep-seabed mining[30]. There is currently little baseline information and no data available for recovery times at inactive vent sites which are most likely to be mined, making predictions difficult[30].

A consideration of scale and placement of mining activity, potential for cumulative impacts from more than one mining operation, and understanding of connectivity in the region are key to prevention of biodiversity loss. For this reason, Regional Environmental Management Plans (REMPs), which the ISA has commenced developing, will be important strategic environmental management tools[41]. The broad purpose of REMPs is to provide region-specific information, measures and procedures in order to ensure effective protection of the marine environment in accordance with UNCLOS. To this end, REMPs should have clear environmental objectives[42], and establish environmental management measures including the designation of protected areas (in ISA nomenclature: 'Areas of Particular Environmental Interest' or 'APEIs') prior to or independent of contract placement. REMPs should also undergo periodic reassessment[43–46], which can be fed into regulatory decisions and actions. REMPs should take into account cumulative effects from multiple mine sites, or synergistic effects from different marine uses or stressors, and seek to manage potential conflicts occurring in the same region. For example, the incorporation of climate representativity and refugia to enhance climate resilience has been proposed as design criteria for APEIs[46]; climate consideration will also ensure that monitoring programs can differentiate climate from mining impacts and inform cumulative impact assessment[47].

It is difficult to anticipate how best to mitigate the potential impacts of deep-seabed mining because the full mitigation hierarchy (avoid, minimize, remediate and offset), considered best practice in terrestrial and shallow-water extractive activities, is unachievable at present in the deep ocean[34,36] and there have been no investigations that reflect the scale of impacts caused by mining activity[38,48]. Challenges associated with restoration include the slow recruitment and growth of deep-sea species, the large-scale disruption of population connectivity, and the limited understanding of the requirements for proper ecosystem functions. Additionally, the likely high cost and technical feasibility of assisted regeneration techniques such as the use of artificial substrates, the transplantation or seeding of larvae, and the artificial eutrophication of the ocean surface, may also be insurmountable[33,34,36]. Proposed restoration strategies have yet to be tested and the financial commitment required

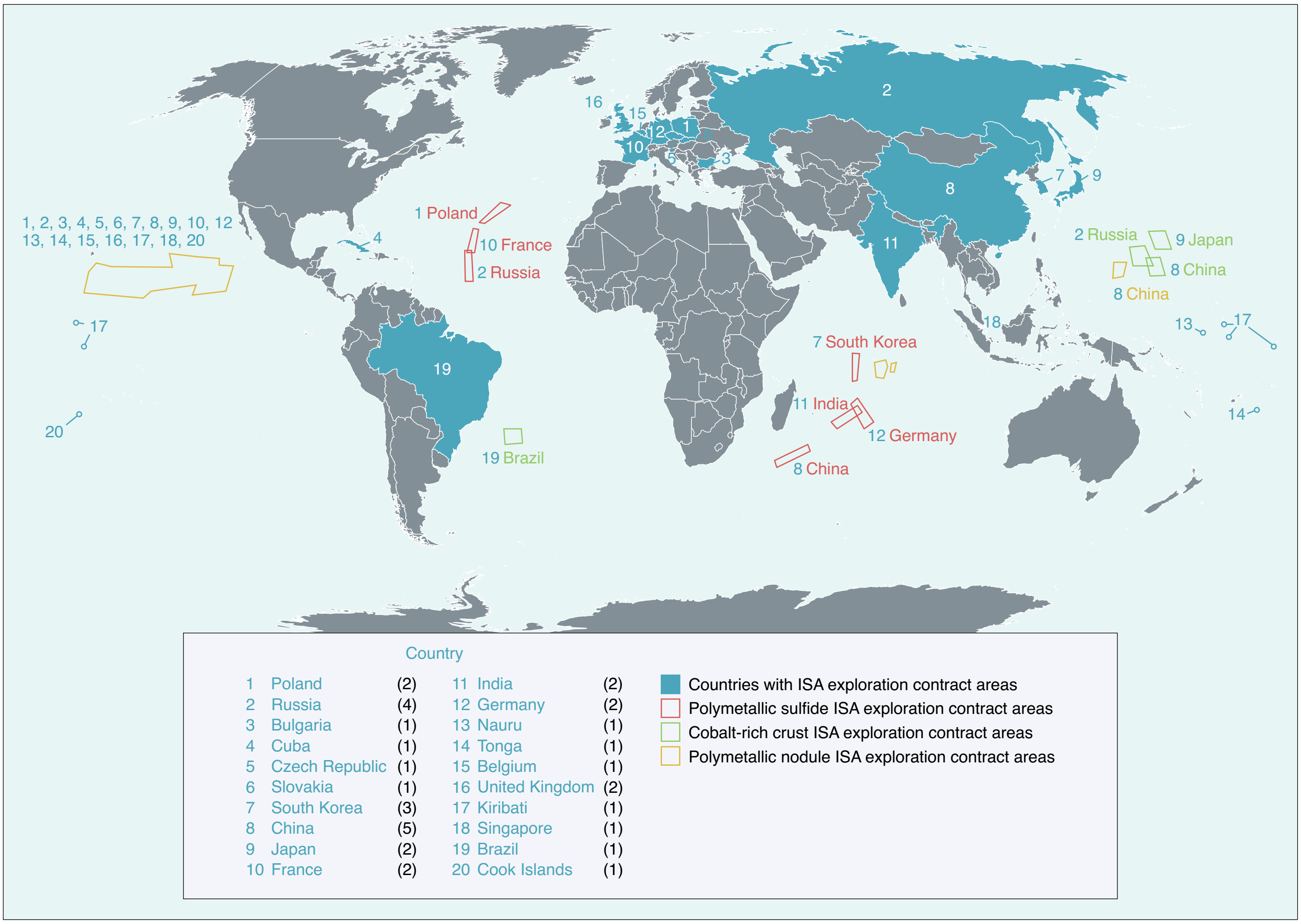


Fig. 2 | International deep-seabed mining exploration contracts and countries. Countries with exploration contracts from the ISA are shown in blue, the number of contracts per country (as of 2019) is given in the legend in parentheses, and the general location of contracts in the Area is shown schematically for different resources (from ref. [95]).

may be extensive[36]. Due to gaps in current ecological knowledge and restoration abilities in the deep sea, offsetting, the last stage in the mitigation hierarchy, appears currently unable to replicate biodiversity and ecosystem services lost through deep-seabed mining[36].

If deep-seabed mining moves forward, it should be approached in a precautionary and adaptive manner to integrate new knowledge, and avoid and minimize harm to habitats, communities and functioning[36]. There are a number of ways in which this might be done, with each option informed by clear objectives, with accompanying indicators and thresholds, and supported by agreed-upon monitoring standards and protocols. APEIs, and preservation and impact reference zones should be designed and monitored in a scientifically valid and statistically robust manner[49], and environmental impact assessments (EIAs) should address requirements to achieve statistical validity. Avoiding harm altogether is unlikely to be achievable given the destructive nature of deep-seabed mining, which will heavily impact the immediate mining sites; disturbed areas would vary among deposit types, but may generally be in the order of tens of thousands of square kilometres of seafloor per year for several decades for polymetallic nodules on abyssal plains[13,32,34,36,38,50]. Some impacts might be avoided at a project level by reducing the footprint of mining within a contracted area and/or by leaving some minerals with associated fauna in place and undisturbed (protected areas or refugia)[26,36,50,51]. Engineering specifications could limit sediment plume dispersal, longevity, and toxicity, to avoid seabed compaction or turbulence, and to reduce light and noise pollution[36]. The industry is in its infancy, and new technological breakthroughs may be possible. The effectiveness of such measures in reducing losses of biodiversity requires testing and will rely upon a strong regulatory framework and monitoring and enforcement capabilities. Adaptive management has been identified as a useful regulatory approach that could be applied to deep-seabed mining operations once other challenges are addressed[52].

Governance and regulatory challenges

Deep-seabed mining poses governance and regulatory challenges at both the state and international levels.

State level. A state should adopt appropriate measures to exercise control over any seabed mineral activities under its jurisdiction. State laws relating to the management of seabed mining should be "no less effective than international rules, regulations and procedures"[53] such as the Mining Code of the ISA currently under negotiation[54]. Direct obligations under international law in respect of seabed mining include applying the precautionary approach, employing best environmental practice, and conducting prior environmental impact assessment[55]. These obligations apply to states regardless of their individual wealth or capacity. A number of states, particularly in the Pacific region, have implemented national legislation to govern seabed mineral activities (both within national and international jurisdiction)[56,57]. It is notable, however, that several states actively engaged in exploration activities as yet have no detailed legal regime in place (for example, India, France, South Korea, Brazil, Russia and Poland)[56,58].

The creation of adequate legislative frameworks by states, while essential, is not sufficient in itself; implementation and enforcement of the rules created are also crucial[55]. This point is supported by international law (for example, UNCLOS Articles 214 and 215), which requires appropriate environmental standards not only to be governed by domestic legislation, but also to be implemented through monitoring and enforcement. Strong institutions are particularly important to the oversight of seabed mining; legal, fiscal and environmental matters will all require dedicated public administration capacity. Provision should also be made for independent oversight and public notification of, and participation in, decision-making[59,60].

All ISA contracts must be held or sponsored by an ISA member state. Contractors are required to hold the nationality or be under the 'effective control' of their sponsoring state or its nationals (UNCLOS Article 153). To date, little scrutiny has been applied to how this relationship has been interpreted in individual sponsorship arrangements[61]. There is also little information in the public domain regarding the contractual arrangements and regulatory measures established by states in relation to ISA contractors whom they sponsor[56].

International level. The ISA is tasked to 'organize and control' contractors to 'secure compliance' with rules set by the ISA, including those designed to deliver on the ISA's mandate to secure the 'effective protection of the marine environment from harmful effects' of seabed mining[53]. Much of the oversight authority within the ISA rests with the Council and with its subsidiary organ, the Legal and Technical Commission (LTC), which provides initial recommendations regarding the ISA's regulations as well as recommendations on applications for mining contracts (Box 2). The Council requires a two-thirds majority, without veto in any of its five chambers, to overturn an LTC recommendation for approval of an exploration or exploitation contract. This majority may be hard to achieve in practice—hence LTC recommendations are highly influential[62]. The composition of the LTC membership is to some extent prescribed by UNCLOS, which requires appropriate qualifications, geographical distribution and an absence of personal financial interest in exploration or mining in the Area. Limited environmental expertise and workload capacity presents challenges for the LTC to meet its duties, involving the review of EIA reports, developing environmental management plans, and drafting environmental management standards and thresholds. While it is recognized that the LTC has been substantively carrying out its duties, with a heavy workload, criticisms have also extended to a lack of transparency, and potential conflict of interests in the LTC[62–64] as well as improper haste in establishing 2020 as a deadline for finalizing the Mining Code[54,65,66].

There is no other precedent of an international intergovernmental treaty body (with 168 members, each with their own political priorities and interests) attempting to act as a minerals licensing, environmental permitting, monitoring and enforcement, and revenue collection agency, as is required of the ISA[67]. UNCLOS also envisages an in-house mining wing of the ISA called 'The Enterprise' (UNCLOS Article 170). When The Enterprise comes into existence, the ISA will be required to issue exploration or mining contracts to, and regulate, itself. These are functions that, within national jurisdictions, are usually performed by different government agencies operating under separate mandates. The ISA also faces constraints from infrequency of meetings, lack of funding, inherent conflicts of interest, and lack of quorum. The ISA, as currently constituted, is a UN-style meeting convener, not a functioning regulatory body; it houses no inspectorate or enforcement capacities. Stakeholders have previously raised concerns with regards to the ISA governance practice and have called for better incorporation of science and external independent expertise in ISA processes[62,64,65,68,69].

Socio-economic and cultural benefits and costs

Deep-seabed mining could bring costs and benefits at both the state and international levels.

Benefits. Deep-seabed mining in the Area will bring increased metal supply to consumers globally, and also revenue to 'humankind', collected and managed by the ISA. UNCLOS provides that this revenue should be equitably shared, "taking into particular consideration the interests and needs of developing States". The amount and form of that revenue will depend on the systems of payments for contractors and benefit-sharing that are currently under negotiation in the ISA. An initial royalty of 2% (rising later to 6%) has been proposed under an economic model developed by ISA consultants, based on contractor profits and data. This would lead to the mining company receiving around 70% of the total project proceeds, and the ISA around 6% (with the remainder going to the sponsoring state or whichever state is receiving profit taxes from the mining company)[70]. Some stakeholders (see Box 3) have expressed concern with the principles and inputs used in that economic model, and the low royalty rate and return to the ISA. Opponents include 47 African member states, who calculated that the proposed payment regime could lead to a return to 'humankind' of less than US$100,000 per annum per country, which they do not deem to be fair compensation for the transfer of the Area's minerals from humankind to private ownership[71]. The international seabed regime established by UNCLOS is predicated on the basis that mining be carried out in such a manner as to "foster healthy development of the world economy and balanced growth of international trade, and to promote international co-operation for the overall development of all countries, especially developing States"[53]. UNCLOS also provides that mining in the Area must not adversely affect the economies of developing countries derived from terrestrial mining or must compensate them (sections 1(5)(e) and 7(1) of the Annex to the 1994 Agreement). This has the potential to limit financial benefits flowing to parties other than the mining contractor, and the compensated country. The African Group of member states at the ISA has expressed the view that a regime that would see benefits from mining in the Area flow principally to developed states, or to wealthy shareholders of companies, who are conducting the mining, should not be permitted[70].

Deep-seabed mining within a state's national jurisdiction or in the Area under a state's sponsorship has the potential to benefit that state by contributing to government revenues (through taxes and/or royalties). The amount may be considerable, especially for a country with a small population such as the Cook Islands[72]. In addition to introducing a new supply of metals, benefits may also include creating jobs and training opportunities, strengthening the domestic private sector, encouraging foreign investment, new technological development, funding public-service or infrastructure improvements, and supporting other economic sectors[57,59].

Other benefits may accrue. Deep-seabed mining has the potential to benefit the exploitation company, shareholders and members of the supply chain through financial profits[73]. Technological innovation is a necessity of this nascent industry and could be another major benefit of these activities. Exploration and impact monitoring may expand scientific knowledge that is currently lacking (if levels of data quality and public-sharing are improved)[74]. Similarly, research associated with deep-seabed mining could also increase understanding of genetic resources, with potential for use in pharmaceuticals, industrial agents, biomedical products or bioinspired materials[35].

Economic development is a key driver for most states, but many resource-rich developing states exhibit slow economic growth. As

Box 2 | The International Seabed Authority (ISA)

The ISA is an intergovernmental agency created by the UN Convention on the Law of the Sea, and whose structure includes the following organs: the Assembly, the Council, the Legal and Technical Commission, the Finance Committee, the Economic Planning Commission, The Enterprise, and the Secretariat.

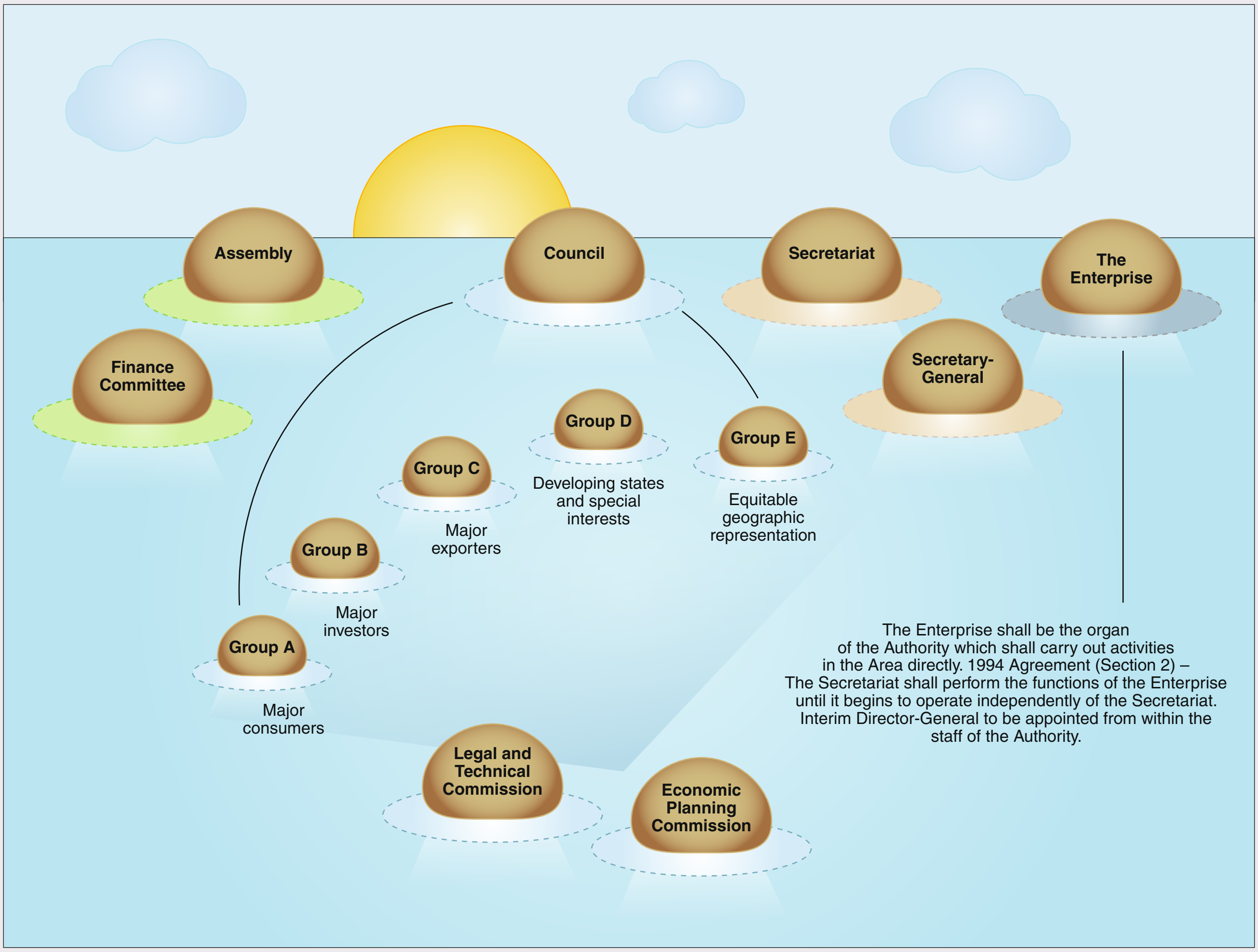
The executive body of the ISA is its 'Council' comprising 36 member states. These states are elected in a number of different 'chambers', designed to ensure a diversity of nations, representing different interests. These chambers include major consumers or importers of the relevant metals, the largest investors in deep-sea mining in the Area, major exporters of the relevant metals from land-based sources, developing countries with special interests (for example, land-locked, geographically disadvantaged, islands), and five regional geographic groupings (Africa, Asia–Pacific, Eastern Europe, Latin America and Caribbean, and Western Europe and Others). (UNCLOS, 1994 Agreement, Annex, section 3, paragraph 15.)

The Council reports to the Assembly, which comprises all 168 ISA member states. Both organs meet at least annually at the ISA's headquarters in Kingston, Jamaica.

The ISA is supported by a Secretariat, also based in Jamaica, headed by a Secretary-General who is the chief administrative officer of the ISA, and required to support all ISA meetings and to perform such other administrative functions as may be instructed (UNCLOS Article 166).

Another key organ within the ISA is the Legal and Technical Commission (LTC): this is a group of (currently 30) experts, serving in their individual capacities, who meet bi-annually with responsibility to prepare recommendations and advisory inputs to the Council. The LTC's mandate includes the provision of recommendations on applications for ISA contracts, and preparing drafts of rules, regulations and procedures of the ISA, for Council consideration or adoption (Article 165).

The Finance Committee oversees the ISA's administrative budget. The Economic Planning Commission is tasked to examine the impacts of mining in the Area on land-based mining economies; its function is currently being covered by the LTC. The Enterprise is envisaged to be an in-house mining arm of the ISA, who will commence operations via joint ventures with other contractors. The Enterprise has not yet been operationalized.



Box 2 figure adapted with permission from Grid Arendal (https://www.grida.no/resources/6311).

with other extractive industries, the large financial gains that may be generated by successful deep-seabed mining, if not handled carefully, could have negative effects on a state's economic status[75]. The risk of this 'resource curse' may be combated by sound revenue management, and an integrated resource management approach, grounded in transparent and non-discretionary policy and law, with

Box 3 | Stakeholders for deep-seabed mining

At this time, those expressing the greatest interest in deep-seabed mining, both actively and passively (and not necessarily always to propel the industry forward) include the following groups:

(1) Nations that have ISA exploration contracts (including China, India, Japan, Russia, South Korea and various EU countries).
(2) Countries that have deep-sea mineral deposits of commercial interest within national jurisdictions (for example, Papua New Guinea, Tonga, Cook Islands, Namibia, Japan and Kiribati).
(3) Countries that actively mine the same minerals on land (for example, Democratic Republic of Congo, Chile and South Africa).
(4) Mining companies that have claims within EEZs or have partnered with states on ISA exploration contracts (for example, Nautilus Minerals, UK Seabed Resources Ltd., Global Sea Mineral Resources, and Deep Green).
(5) Research institutions and scientific networks (for example, JPI Oceans, the Deep-Ocean Stewardship Initiative, and the Deep Ocean Observing Strategy) interested in bringing science to decision-making and the development of regulations, and in providing sustained observations that can help address outstanding scientific questions.
(6) States, environmental advocacy groups, intergovernmental organizations (IGOs) and non-governmental organizations (NGOs) focused on conservation and biodiversity maintenance (for example, the International Union for Conservation of Nature, Deep-Sea Conservation Coalition, Greenpeace, WWF, and The Pew Charitable Trusts).
(7) Other components of the blue economy such as the deep-sea fishing industry and underwater cabling companies with potential conflict or spatial overlap.
(8) Civil society and religious groups that are largely active locally and are wary of exploitation of local and indigenous people and threats to their local environment and culture (for example, the Holy See, Deep Sea Mining Campaign, the Pacific Conference of Churches, Alliance of Solwara Warriors, Fair Ocean, Misereor, and Brot für die Welt).

sovereign wealth funds that are used both for long-term investments in infrastructure or socio-economic projects, and also safeguarded for future generations (‘intergenerational equity’)[59].

The ISA has a different revenue management challenge: how to distribute the proceeds from mining in the Area equitably, and for the benefit of all of humankind[76]. Built into the concept of the common heritage of humankind is the principle of intergenerational equity[77]. The idea of partitioning resources among current and future generations is an important component of sustainability for non-renewable resources. This potentially complex aspect of the ISA’s regime has received little attention to date. Different models may include direct distribution of a share of proceeds to individual member states, or to an ISA-managed fund, invested in the long-term with a view to extend the common heritage benefits over time to future generations[77], to which states can apply for grants[41]. However, the proceeds available for distribution may not be large amounts[71] and may also be depleted by the need to cover operational costs of the ISA[78].

Costs. There have been calls for cost–benefit analyses for deep-seabed mining projects (https://go.nature.com/2Msfcoj). Some social cost–benefit analyses have been conducted for mining using Pacific Island case studies[72,79], though criticized given the difficulty of quantifying little-studied impacts and ecosystem services such as food, biomaterials, climate regulation or nutrient recycling[35,57,80,81]. Analyses generally focus on the benefits of seabed mining being economic, and the ‘costs’ ecological. There may, however, also be economic costs to a state engaging in a deep-seabed mining operation that loses money (for example, https://go.nature.com/3066UKN) or incurs liability for third-party harm[82], and in regulating it[57,72].

Trade-offs are also hard to quantify. Disruptions caused by deep-seabed mining in the ocean and on land can cause conflict with other economic sectors and threaten loss of non-market ecosystem services[21]. The value of lost ecosystem services due to mining impacts could appear in the financial code as some form of monetary compensation (for example, to the common heritage of humankind) or be factored into the amount of the royalty payable by the miner. As with land-based extractive industries, seabed mining has given rise to concerns that disruption of fragile ecosystems, impacts on other sea uses, failure to respect the rights of indigenous peoples, or impacts caused by associated land-based activities will adversely affect local communities’ property, livelihood, food sources and lifestyle[59,83]. Noise, light, sediment plumes, and contaminants can threaten both commercial and subsistence fisheries[11,12]. It is also possible that mining could prevent future use of the mining site for other purposes. Seafloor substrates targeted for mining may hold genetic resources that could be lost[26,35]. Deep-seabed mining could cause disruption of carbon cycling by removal of autotrophic microbes that fix carbon, and fauna that bury carbon in sediments[28]. Loss of tourism from the threat of mining is feared in diverse settings such as Papua New Guinea, Fiji, Portugal and Spain[21]. It has also been noted that deep-seabed mining may cause a loss of cultural or spiritual value associated with a pristine ocean, or traditional sense of ownership of or identification with the ocean and its resources[57]. For seabed mining, concerns have also been expressed about transboundary impacts, whereby a mining operation within one jurisdiction causes deleterious effects to the marine environment or coastal communities of a neighbouring country[84]. The international legal framework currently contains lacunae with regards to identifying and enforcing liability for compensation, clean-up or remediation[55,82]. Since no full-scale mining impacts have occurred, the nature and extent of these trade-offs cannot be studied and thus remain speculative. It is noted also that many of these concerns apply similarly to land-based mining.

Looking to the future

Most discussions of deep-seabed mining address where, when and how to conduct deep-seabed mining and what the impacts may be, not whether to mine[85]. Civil society and the public have had limited voices to date[86], though there have been a number of calls for a pause or moratorium on seabed mining, relying on arguments that adverse effects on the environment will outweigh the benefit of additional metals[85], or seabed minerals are not needed[87], or that more time would enable the scientific study and regulatory capacity-building necessary before rules can be set or implemented with requisite degree of confidence (for example, the European Parliament in 2018, the UK House of Commons Environment Audit Committee, the Long Distance Fleet Advisory Council of the EU[88], the UN Envoy for Oceans, and Fiji, Vanuatu and Papua New Guinea governments). At the other end, there is the stance that deep-seabed mining should be facilitated and incentivized. It is notable that no requests for exploration contracts have been denied by the ISA thus far, and there is a current push to develop the Mining Code by 2021 so that exploitation may commence[66].

Deep-seabed mining is certainly a sustainability conundrum. Terrestrial mining has major environmental and social impacts[8] including the displacement of communities, contamination of rivers and groundwater from tailings, damage to communities from tailings slides, violation of land rights, community repression, and unfavourable child labour/slavery practices[89]. These could all be improved with focused effort, but presently add incentive to look to the ocean as an alternative source of minerals[7,19]. A substantial shift in current metal production patterns could have geopolitical implications, particularly for countries that are currently major metal producers (for example, Democratic Republic of Congo, Chile, China and South Africa) (Table 1). Alternatively, mining in the Area may occur in addition to terrestrial mining for the same metals, which would not displace adverse impacts of on-land mines, and an increased supply of minerals could drive metal prices down.

Unlike terrestrial mining, deep-seabed mining is beset by extreme knowledge gaps that could disable proper regulatory practices, particularly in understanding how deep-ocean ecosystems will respond to industrial-scale disturbance. There is an inherent conflict between a duty to protect the marine environment, and a call to mine the deep sea for metals, with the remote nature of the deep ocean and its unfamiliarity to most people raising the challenge of ensuring inclusive stakeholder participation to inform decisions taken at the international and state level (see Box 3). How society moves past these crossroads, and the decisions taken on behalf of humankind by governments at the International Seabed Authority, will likely have a lasting impact on our oceans.

One option would be to slow the process of transitioning from exploration to exploitation. This will allow the necessary time to agree and execute a road-map to build the regulatory capacity of the ISA to ensure the effective protection of the marine environment from the impacts of mining in a transparent and inclusive manner, including the creation of environmental consents, evidence, inspectorate and enforcement functions. It would also allow for the establishment of an international research agenda and timeline, to collect and synthesize high-quality, deep-sea scientific data to fill identified gaps in knowledge required for decision-making and environmental management, before any deep-sea mining takes place. Further research would facilitate the identification, declaration and enforcement of spatial protections (for example, biologically representative, fully protected no-mining zones established in perpetuity prior to any award of exploitation contracts, across all ocean regions under ISA jurisdiction), and would enable states to demonstrate efforts towards their international duties to ensure the effective protection for the marine environment from mining's harmful effects (UNCLOS), to achieve in situ conservation (Convention on Biological Diversity), and to conserve a percentage of marine areas (Sustainable Development Goal 14.5 and Aichi Target 11). More time could allow new opportunities to emerge for industry and scientists to partner on testing technological and conceptual innovations for minerals recovery that minimize harm to the marine environment. More time may also allow broadened societal discussions of mining in other international fora beyond the ISA, for example at the UN General Assembly, at the conferences of the Convention on Biological Diversity or international ocean conferences.

Another key factor may be future implementation of a circular economy, which acts through improved product design, reduced demand, reuse, recycling, reclassification of materials, and use of renewable energy for production[90]. For metals targeted by deep-seabed mining, this would require independent research and long-term planning with attention focused on Life Cycle Sustainability Analysis[91]. Alternative energy technologies are already under investigation that reduce the use of lithium, silver, neodymium and dysprosium. Redesign is required to avoid additives that improve product quality and durability but make metal recovery from electronic products more difficult[92]. More government policy focus, consumer awareness, and the creation of incentives and reduction of barriers to promote behaviour change to favour a less mineral intensive renewable energy system could also be crucial.

Ultimately, society will have to make choices in order to meet the needs of an increasing population while achieving a low-carbon emission future. How we choose to balance environmental impacts and economic benefits from mining on land versus the ocean, whether to engage in the behaviour changes required for a circular economy, and the weight given to precaution and uncertainty, will depend in part on political, industry and civil-society awareness of the issues, the extent of stakeholder engagement, and degree of regulatory competence. Open dialogue, sound governance and science-informed decision-making may assist humankind to navigate these challenges.

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Author contributions

L.A.L. initially conceived the manuscript and developed the figures and tables. L.A.L., D.J.A. and H.L. wrote the manuscript together.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence should be addressed to L.A.L., D.J.A. or H.L.

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