

S1 Table: List of environmental indicators

Risk Indicators	Components	Description
Biodiversity risk	Loss of Species and ecosystem	DSM is predicted to result in intense damage to few of the world’s pristine habitats, many of which are ecologically and biologically significant areas with biodiversity hotspots [1]. The most direct DSM impact would be species loss/fragmentation, loss of ecosystem structure and function. Furthermore, the damages caused to deep-sea ecosystems are most likely to be permanent [2].
	Biodiversity threats	Mining affects the cetaceans and tourism industry which is highly dependent on whale watching. Mining on environment like this with such high degree of uniqueness and endemism will impact the biodiversity greatly, which will also be difficult to reverse [3].
	Marine ecosystems and biodiversity risk	While the Norwegian government insists that it can conduct deep-sea mining in a sustainable way, critics say that these activities will put the marine ecosystems and biodiversity at risk [4].
Vulnerability to coastal states	Vulnerability to coastal states	Mining is about to threaten the small island developing states (SIDS) surrounding the CCZ, which have already been threatened by continuous rise in sea levels [5]. As sea levels rise, additional stress from mining activities could lead to increased coastal erosion and habitat loss, exacerbating the challenges these nations face [6]. This intersection of deep-sea mining sector and climate change thereby tend to complicate the scenario for SIDS.
Pollution	Pollution outreach from area to adjacent states	Pollution discharged by TMC in its Tonga sponsored license area is expected to reach Hawaiian and Kiribati waters in just three months. The mining operations are expected to destroy an area of seabed equivalent to the land area of the whole of Hawaii in the 30-year license period [7], if granted, given the potent of discharge plume to

		travel over 1,400km. DSCC [5] further highlights that the word adjacent, may not cover all the affected states and therefore potentially affected states may therefore not be adjacent, indicating much broader implications of DSM on the coastal states.
Troublesome sea life	Disturbing sea life of neighboring territories	The "troublesome sea life" indicator serves to highlight the potential disturbances to marine ecosystems that may arise from DSM operations. These disruptions can appear as sediment plumes, poisonous metals, and 'dust clouds,' all of which can harm marine creatures [8–10].
Knowledge gaps	Knowledge gaps and inadequate research	The Norway Institute of Marine Research (IMR) said that the government had made assumptions from a small area of research and applied it to the whole area planned for drilling. There is currently not enough knowledge needed to extract minerals from the seabed in the manner required and a period of 5 to 10 years of research into impacts on species will be needed, to know the exact impacts of DSM. These knowledge gaps on this nascent sector might demand more investments from the private sectors to carry out research on the deep marine environments [11].
	Poor scientific knowledge and unforeseen impacts on marine ecosystem	Opponents of DSM emphasize that scientific knowledge of the ecosystem in deep sea and other marine environments are poorly understood. Moreover, DSM relies on naïve/untested technologies that may result in unforeseen and long-lasting impacts to the marine ecosystems by changing the characteristics of the seabed and leading to habitat changes [12].
Greenwashing argument	Greenwashing argument	The urgency of mineral scarcity necessitates a shift towards recycling as a primary source of critical minerals, rather than relying on new extraction methods that could exacerbate environmental degradation [13]. By prioritizing DSM which tends to be extractive and unsustainable, there is a risk that policymakers and industries may overlook the potential of recycling existing materials, which could provide a more

		sustainable and less environmentally damaging solution to mineral shortages [8].
Ambiguous guidelines	Lack of clear guidelines in practical application of precautionary principle	Papua New Guinea (PNG) still lacks a clear set of guidelines in implementing the precautionary principle within their regulatory framework. It was evidenced through the solwara 1 project, where they didn't apply the precautionary principle in practical aspects though uncertainty on environmental effects existed along with lack of data [14].
Habitat risk	Ocean habitat risk	Mining techniques may cause significant noise and light pollution, disrupting the habitats of organisms' dependent on seabed nodules [2] as they involve the removal of large volumes of sediment and rock. This further threatens the survival of certain biota, eg: the gastropod <i>Dracogyra subfusca</i> , which is already facing risks due to ongoing exploration activities in hydrothermal vent field [15].

S2 Table: List of economic indicators

Risk Indicators	Components	Description
Private profit over public good	Company monopoly	Mining companies have market capitalization values, greatly in excess of many small countries annual GDP and can draw upon global sources for legal and negotiation purposes [16]. Though the seafloor tends to be the common heritage of mankind, the current scenarios reflect the formation of monopoly [17].
	Business sided profits	The estimates of the cost benefit analysis models (MIT) indicate a higher benefit to miners (nearly thrice) than that of the ISA from where the benefits flow to mankind as a whole. The opponents and environmental warriors claim that DSM would benefit only a small number of people, making the rich richer and in no way will bring prosperity to the indigenous communities [18,19].
Risk on commercial fisheries	Impact on fisheries	DSM in the Pacific could have irreversible impacts on ocean-dependent communities, particularly the world's largest tuna industry. Contamination of seafood near mining sites and increased activities near spawning areas could affect fisheries stocks. Due to the high migratory nature of tuna, the impacts in one region have the potential to be transmitted to other regions that are unaffected by mining but rely on the fishing business [20].
	Threats to commercial fisheries	Deep-sea mining impacts may intersect with other industries, such as the fishing industry which is significant for the economy of many countries. Conflict between fisheries and DSM will occur given the existing spatial overlap within and around CCZ. The suspended sediments and discharge waters with heavy metals impacting pelagic communities will have direct consequences on the fishing industries if the target species are directly or indirectly impacted. DSM impacts tuna fisheries through discharge water and plumes containing heavy metals, mining noise and increased density of mining vessels operation which will limit fishing vessels operation [21].

Ecological cost	Cost for ecological impacts	The estimated cost associated with unavoidable ecological impacts to benthic communities due to mining activities (\$500,000) and unplanned releases are very high ranging up to \$28.6 million [22]. The question of who is to bear this burden in case of its occurrence remains unanswered till now.
	Higher costs associated with environmental degradation	DSM is said to result in increased environmental and post closure costs, with the profitability expected to be marginal. Moreover, the costs linked to offsetting environmental degradation in the deep-seabed including post-closure remain largely unknown, highlighting the risks on investors to be very high [23].
Technological cost	Technological advancements	Innovative technologies such as sodium-ion batteries can potentially mitigate demand for critical minerals, together with the rise of mature battery chemistries requiring lower amounts of critical metals, such as lithium iron phosphate (LFP). While low critical mineral prices help bring battery costs down, they also imply lower cash flows and narrower margins for mining companies [24].
	Constraints in technology development and financial potential	Developing states, including Least Developed Countries (LDCs), Landlocked Developing Countries (LLDCs), and Small Island Developing States (SIDS), face significant hurdles due to a lack of advanced technology and financial resources, which, combined with revenue risks and acute poverty, discourage investment in DSM [25,26].
Loss and profitability risks	Risk of loss and liability	The risks of losses and liabilities in a developing country's business scheme governed by international laws, regulations, and competencies are of the same standards as developed countries. For example, under the current rules, a developing country like Tonga is liable for the damage if it fails to fulfil its obligations as a sponsor, for which it has to maintain highest standards of environmental safety. This would ultimately put the Tongan taxpayers at burden [27,28].

	Loss of investment	Officials in PNG emphasize that the country had a 15% stake in Nautilus Minerals prior to its bankruptcy. PNG still stands to lose all of that reported \$120 million investment in the company, unless it terminates the license [29].
	Risk of reduced benefit	Allowing for DSM in the sulfide deposits in PNG has the potential to improve the well-being of the people in these nations [22]. However, Nautilus Minerals' failed DSM project in PNG has encountered financial challenges and public rejection as well [30–32].
	Lower success rate/profitability	The success rate of DSM is doubtful as it does not tend to have significant cost advantage over land-based mining at current and projected factor prices [33]. It is also critiqued to lead to worse impacts than land-based mining for its operation in new environments [34].
Tourism	Impact on tourism industry	Mentioned as one among the potential impacts of DSM on people, the environmental degradation resulting from the mining activities might have subsequent impacts on the tourism industry [31]. The potential loss of unique marine species and habitats can diminish the aesthetic and recreational value of these areas, leading to decreased tourist interest and revenue [35].
Royalty payment regimes	Unacceptable royalty payment regimes	The African Group does not support the time varying royalty including rates of 2%/6% or the price varying royalty if the suggested rates are proposed to be 2%/5% to 9% in the royalty payment regimes. It is because, these payment regimes neither results in fair compensation to mankind nor maximise the ISA revenues and subsidise DSM relative to land-based mining [36].
Knowledge gap on EAF	The Economic Assistance Fund: Lacking knowledge	The percentage of shares from DSM that will be available for distribution as a compensation to the terrestrial mining countries from the EAF (Economic assistance fund) is still under negotiation/discussion, given the lack of research to date on this matter and the conceptual and practical difficulties associated with payment calculation. It

		is therefore still unknown to what extent they will be compensated for the economical loss [37].
Terrestrial mining vs DSM	Competing interest with terrestrial mining countries	The countries producing DSM minerals will be competing with the major African states that are land-based producers of copper and cobalt, including Zambia, Botswana, Morocco, Madagascar, Gabon, South Africa, Namibia, Democratic republic of Congo and Zimbabwe. Surplus mineral resources in the market and fall down of prices will adversely affect the economy of these land-based mining countries [38,39].
Multiple shareholders	Complexity with multiple shareholders	Though on paper, TOML is Tongan, it is financially controlled by Canada and management wise by both Canadians and Australians [27].
Lack of special provision	Lack of specific clause	Whether it is developing or developed countries, the rules apply equally for the sponsoring countries and there is no special provision under international laws in ISA for the developing country like Tonga, where they are completely responsible for mining damage caused to ocean floor on the same level of culpability as developed countries [28].
Contractual violation	Risk economic loss due to contractual violation	In case if the subsidiary, Tonga Offshore Mineral Limited, violated its contractual obligation with the ISA, Tonga might be left with a heavy bill to pay which is an additional concern for the country as the environmental damage itself far outweighs the benefits [40].

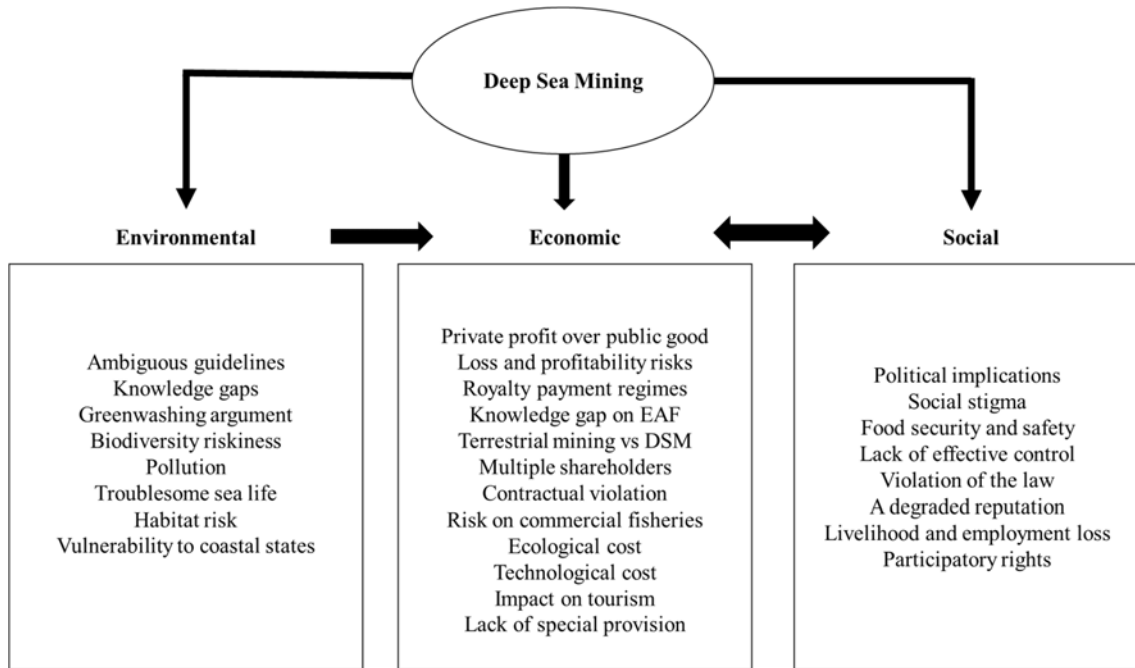
S3 Table: List of social indicators

Risk Indicators	Components	Description
Political implications	Political volatility	The "political implications" risk indicator examines how DSM activities might influence geopolitical and security dynamics. For example, the Clarion-Clipperton Zone (CCZ), located in international waters, is strategically significant for countries such as Russia, China, and the US. Political volatility between these countries could lead to geopolitical tensions [41].
	Geopolitical implications	Norway's decision of entering DSM could have geopolitical implications. The launch of Arctic mining would increase the international competition for resources and change the dynamics of the region [8].
Social stigma	Loss of cultural and heritage values	Deep sea mining threatens the cultural, heritage and spiritual values associated with pristine ocean and sentimental beliefs of the indigenous communities. These communities believe that the deep sea and its seabed are intimately connected to humanity despite the geographical distances involved. According to them, DSM disturbs the sense of who they are including the spirits that inhabit their culture and beliefs [42].
	Lack of societal acceptance	Different aspects of social acceptability have contributed to conflict situations and ultimately the demise of the DSM project, as happened in the case of Solwara 1. Financial issues related to foreign companies, asymmetry in power balance between pacific states and global business, governance challenges, lack of community and stakeholder acceptance were the critical factors in the negative perception of societal acceptance [43].
	Lack of consent from citizen	There are no governance procedures in Tonga where the state conscientiously informs the public about the project happenings to gain their consent, particularly those which might affect their land and territories. The government policy also fails to

		ask public opinion on denationalizing deep sea minerals when calculating the cost and benefits to the country [28] .
Food security and safety		Although the fishing activities of most countries have minimal overlap with the proposed mining sites, there are a number of countries, particularly developing or small island states, that could experience significant impacts on their fishing yields. Research reveals that in certain regions, up to 10 percent of the catch may be affected, leading to substantial decreases in the economy and food security of these countries [44]. Seafood caught near mining sites could be contaminated with toxic metals impacting seafood safety [45,46].
Lack of effective control		Sponsoring states must have effective control over the companies they sponsor, but the ISA has not explicitly defined what that means. For eg: TOML’s exploration contract says that if control changes, it must find a new sponsoring state [27].
Violation of the law		a. Norway’s decision on deep sea mining could be a “violation of the law” due to a lack of scientific evidence needed to assess the environmental impacts of future mining activities, which is legally needed for such decisions to be made [4]. b. Norwegian law firm Wilkborg Rein said that passing the bill with an inadequate environmental assessment could violate not only the country’s own laws on environmental protection, but also European and international laws [8].
A degraded reputation		Norway has become the first country in the world to open up its seabed for commercial DSM, despite warning from scientists and experts on environmental concerns. This decision of DSM thereby might act as an irrevocable black mark on Norway’s reputation as a responsible ocean state [47].
Livelihood and employment loss	Livelihood and employment loss	Marine mining, in the short to mid-term is relatively a small part of the total blue economy [23]. As DSM activities expand, they pose risks to marine ecosystems challenging the sustainability

		of other blue economic sectors, particularly fisheries and tourism, which often relies on healthy coastal and marine ecosystem. This in turn leads to significant implications for the livelihood and employment opportunities of communities dependent on these sectors due to the economic hardships they face upon mining, resulting in increased unemployment and social instability [6].
Participatory rights	Inadequacy of Participatory rights	The "participatory rights" risk indicator points out the inadequacy in ensuring procedural rights under the current legal regime for DSM. Integrating indigenous people into DSM management is not just a mere issue of a 'participatory approach' as acknowledged in various international projects and established in some regulations of Pacific States; but is the very foundation of holistic custom-based relationships. Yet, in state like PNG, there is a notable lack in participation of stakeholders, common public and fishing communities during the decision-making process for DSM projects, which would be philosophically problematic for Oceanian society [31,48].

S4 Diagram. Interconnected risk assessment indicators of deep-sea mining



S4 Table: Score calculation for circular solutions

N	Ref	FS	T	M	BD	CT	PL	SL	HB	PL	SS	FS	VL	LE
o			M	N		S	N					S		
1	[49]	1					1					1		1
2	[50]	1	1		1		1	1	1			1		1
3	[51]													1
4	[52]	1			1		1		1		1	1		1
5	[53]	1			1		1	1	1	1	1	1		1
6	[54]	1	1		1	1	1	1	1	1	1	1	1	1
7	[55]	1	1			1	1	1	1	1	1	1		1
8	[56]			1			1							
9	[57]	1		1	1	1	1	1			1			1
10	[58]	1		1	1		1			1	1	1	1	1
11	[59]						1							1
12	[60]	1	1		1	1	1	1	1		1	1		
13	[61]	1			1	1	1	1	1	1	1	1		1
14	[62]				1						1	1		1
15	[63]	1	1	1	1	1	1	1	1	1	1	1		1
16	[64]	1	1	1	1	1	1	1	1	1	1	1	1	1

17	[65]	1	1		1		1			1	1	1	1	1
18	[66]	1	1	1	1		1	1	1	1	1	1	1	1
19	[67]	1	1		1	1	1	1	1		1	1	1	1
20	[68]	1		1	1		1	1	1	1	1	1		1
21	[49]	1		1								1		1
	Total	17	9	8	15	8	18	12	12	10	15	17	6	19
	Score	0.8	0.4	0.3	0.7	0.38	0.8	0.5	0.5	0.4	0.7	0.8	0.2	0.9
		1	3	8	1		6	7	7	8	1	1	9	0

Ref: References, FS: fisheries, TM: tourism, MN: mining, BD: biodiversity, CTS: coastal states, PLN: pollution, SL: sea life, HB: habitat, PL: political, SS: social stigma, FSS: food security and safety, VL: violation of the law, LE: livelihood and employment.

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