frontiers in Marine Science

POLICY BRIEF
published: 11 December 2018
doi: 10.3389/fmars.2018.00480

Seabed Mining and Approaches to Governance of the Deep Seabed

Kirsten F. Thompson[1†], Kathryn A. Miller[1,2†], Duncan Currie[3], Paul Johnston[2] and David Santillo[2]*

[1] Biosciences, College of Life and Environmental Sciences, University of Exeter, Exeter, United Kingdom, [2] Greenpeace Research Laboratories, College of Life and Environmental Sciences, Innovation Centre, University of Exeter, Exeter, United Kingdom, [3] Globelaw, Christchurch, New Zealand

OPEN ACCESS

Edited by:
Alex David Rogers, University of Oxford, United Kingdom

Reviewed by:
Mustafa Yucel, Middle East Technical University, Turkey
Stanley Kim Juniper, University of Victoria, Canada
David Freestone, The George Washington University, United States

****Correspondence:***
David Santillo
d.santillo@exeter.ac.uk

[†] These authors have contributed equally to this work

Specialty section:
This article was submitted to Deep-Sea Environments and Ecology, a section of the journal Frontiers in Marine Science

Received: *09 May 2018*
Accepted: *29 November 2018*
Published: *11 December 2018*

Citation:
Thompson KF, Miller KA, Currie D, Johnston P and Santillo D (2018) Seabed Mining and Approaches to Governance of the Deep Seabed. Front. Mar. Sci. 5:480. doi: 10.3389/fmars.2018.00480

Commercial seabed mining seems imminent, highlighting the urgent need for coherent, effective policy to safeguard the marine environment. Reconciling seabed mining with the United Nations Sustainable Development Goals will be difficult because minerals extraction will have irreversible consequences that could lead to the loss of habitats, species and ecosystems services. A dialog needs to take place around social, cultural, environmental and economic costs and benefits. Governance of human interactions with the seabed is fragmented and lacks transparency, with a heavy focus on facilitating exploitation rather than ensuring protection. In the light of high uncertainties and high stakes, we present a critical review of proposed policy options for the regulation of seabed mining activities, recommend actions to improve seabed governance and outline the alternatives to mining fragile deep-sea ecosystems.

Keywords: deep sea mining, marine biodiversity, marine policy, marine protection, seabed disturbance, seabed resources, circular economy, mitigation strategies

INTRODUCTION

Seabed mining was first mooted in the 1960s, when John L. Mero implied in his 1965 book, 'Mineral Resources of the Sea', that manganese nodules grow so fast that the supply would be inexhaustible (Glasby, 2000). Research shows that those estimations were incorrect: marine minerals such as manganese nodules grow at a rate of just several mm to cm per million years (Halbach et al., 1980; Gollner et al., 2017). Commercial seabed mining to target these and other slow-growing deep-sea mineral deposits is now a real possibility. Interest is also growing in metal deposits that accumulate at hydrothermal vents on the seafloor. Mining at vents may become a reality even sooner than on nodule fields. In February 2018, Nautilus Minerals completed trials[1] of the deep-sea mining machines it plans to deploy in waters off Papua New Guinea before 2020 and, in March 2018, announced the launch of its seafloor production vehicle[2]. In September 2017, Japan Oil, Gas and Metals National Corporation and the Japanese Ministry of Economy, Trade and Industry announced that it had completed successful trials of polymetallic mineral extraction from a depth of 1600 m off the coast of Okinawa, Japan (Cuyvers et al., 2018). These two examples indicate the urgency to establish a legal framework to ensure effective protection of the marine environment before commercial activities are considered.

Anthropogenic seabed activities are governed either by the national jurisdiction of a coastal State or, in the areas beyond national jurisdiction (the 'Area'), by the International Seabed Authority (ISA) (**Box 1**). The three main seabed mineral resources of interest are cobalt-rich crusts, manganese

[1] http://www.nautilusminerals.com/irm/PDF/1964_0/NautilusCompletesSuccessfulTrialsinPNG
[2] http://www.nautilusminerals.com/irm/PDF

BOX 1 | Current framework of the International Seabed Authority.

The International Seabed Authority (ISA) was established in 1982 under the United Nations Convention on the Law of the Sea (UNCLOS) with the specific purpose to regulate and control activities related to seabed minerals in the area beyond national jurisdiction (the 'Area'). The ISA came into existence when UNCLOS entered into force in 1994. The ISA is comprised of an Assembly, a Council, and a Legal and Technical Commission, as well as a Finance Committee and a Secretariat. The Assembly, the supreme organ of the Authority, is composed of all States Parties to UNCLOS. Council consists of 36 members of the Authority (which are the same as States Parties) elected according to a complicated formula related to consumption and production of minerals and special interests, such as landlocked countries. The Legal and Technical Commission is currently composed of 30 individual members elected by the Council. While the Assembly and Council are open to observers, the Legal and Technical Commission holds its meetings in closed session, despite having been encouraged by Assembly to hold more open meetings to allow for greater transparency (Assembly resolution ISBA/23/A/13 (18 August 2017)). In addition, the so-called Enterprise is empowered to conduct exploration and exploitation of seabed minerals on behalf of the international community but no steps have yet been taken to set the Enterprise into motion.

The ISA has entered into 29 contracts for exploration: 17 for polymetallic nodules in the Clarion-Clipperton Fracture Zone and Central Indian Ocean Basin, 7 for polymetallic sulfides in the South West Indian Ridge, Central Indian Ridge and the Mid-Atlantic Ridge and 5 contracts for cobalt-rich crusts in the Western Pacific Ocean (ISA, https://www.isa.org.jm/deep-seabed-minerals-contractors. Accessed 2 April 2018). The ISA has developed regulations for exploration of the three main types of minerals, and is currently in the process of developing regulations for their exploitation.

Measures developed in the ISA apply only to the Area: regulation on the continental shelf is for the coastal State. As stated in UNCLOS article 208.3: "Such laws, regulations and measures shall be no less effective than international rules, standards and recommended practices and procedures."

nodules and seafloor massive sulfides. Within continental shelf areas, additional resources include phosphorites, ironsands and diamonds. No commercial deep seabed mining has yet taken place, but Nautilus Minerals and Diamond Fields International have obtained permits to extract minerals in the Bismarck Sea and Red Sea, respectively. Nautilus Minerals is "committed to developing the world's first commercial high-grade seafloor copper–gold mine at the Solwara 1 project site in the first half of 2019, subject to further financing"[3]. At the time of going to press, a spokesperson from Nautilus confirmed that because of finance and other delays, "the timing for initial production at the Solwara 1 Project is expected to be delayed past Q3 2019" (pers. comm., N. Dillane, Corporate Communications Manager. Nautilus Minerals). The Diamond Fields International project to mine the metalliferous muds of the Atlantis II Deep site in the Red Sea is on hold due to a legal dispute.

A growing consensus among marine scientists is that at any scale seabed mining will systematically deplete resources, disturb, damage or remove structural elements of ecosystems, cause biodiversity loss and impact ecosystem services (Le et al., 2017; Van Dover et al., 2017; Boetius and Haeckel, 2018). The scale of potential damage is unknown and hard to predict because our understanding of deep-sea marine biota remains limited. Also unknown is the extent to which an ecosystem will recover when mining ceases and over what timescales (Jones et al., 2018). Deep-sea species are inherently vulnerable to environmental change. Characteristics of deep-sea organisms include increased longevity, slow growth rates, reproduction late in life and low fecundity (Carreiro-Silva et al., 2013; Levin et al., 2016; Danovaro et al., 2017b; Montero-Serra et al., 2018). These particular life history strategies mean that many deep-sea species have an increased sensitivity to human activities such as mining, fisheries and climate change. Knowledge gaps have led researchers to urge caution and adopt the precautionary approach to seabed mining (Lallier and Maes, 2016; Boetius and Haeckel, 2018). The place of seabed mining within the United Nations Sustainable Development Goals, in light of the needs for effective protection of the marine environment, transparency, accountability and a full cost–benefit analysis, is increasingly under debate (Kim, 2017).

In Miller et al. (2018), we presented a general overview of seabed mining, including the target minerals, locations, extraction methods, likely impacts and the current state of the industry. Here we collate and review policy options that have been proposed by others to regulate and manage seabed mining activities and suggest actionable recommendations for effective governance and protection of deep-sea ecosystems from human exploitation. Finally, we examine alternatives to marine mineral extraction through a discussion encompassing a circular economy and the need for a global reduction in consumption of technological goods.

POLICY OPTIONS, IMPLICATIONS AND EVALUATION

Industry

Despite the known and irreversible consequences of seabed mining, one concern of many marine scientists is that the mining industry will progress to large-scale extraction without the implementation of adequate measures to avoid significant environmental harm (Levin et al., 2016; Niner et al., 2018). Debate frequently focuses on how to carry out mining rather than whether it should proceed (Woodwell, 2011). To date, no commercial-scale mining trials have been undertaken, therefore making meaningful predictions of the effects of deep seabed exploitation is challenging. Small-scale seabed disturbance trials including DISCOL (disturbance and recolonization experiment) and the MIDAS project (managing impacts of deep-sea resource exploitation) found that recolonization of disturbed seafloor areas will be on decadal timeframes or longer (MIDAS, 2016). Studies report that some recovery of species and habitats is possible after experimental disturbance, but the extent of recolonization is variable and depends on the faunal group studied, habitat and type of disturbance (Jones et al., 2017).

From an historical perspective, Glasby (2000) describes how, in the 1970s and 1980s, interest in deep-sea minerals was growing and that seabed deposits were introduced as a limitless resource that would yield economic benefits to the global community. Discussions to establish the United Nations Convention on the Law of the Sea (UNCLOS) began in the early 1970s as

[3]http://www.nautilusminerals.com/irm/PDF/1935_0/NautilusMineralsannouncesfinancialresultsforQ32017

an international treaty to manage the seas and was formally signed in 1982. The assumption that seabed mining can be a viable source of minerals may arise in part from the historic wording of UNCLOS, which came into force in 1994, and its framework of the ISA. In Article 140, UNCLOS stipulates that activities within the Area are to be carried out for "the benefit of mankind as a whole" (United Nations Convention on the Law of the Sea [UNCLOS], 1982). Currently, the ISA interprets 'benefit' primarily in economic terms and has not addressed if and how resources recovered from the Area could be distributed globally and equitably (Kim, 2017). Social and environmental impacts, costs and any benefits of activities in the Area were neither properly recognized nor fully appreciated when UNCLOS was being negotiated. Costs or benefits that stretch intergenerationally are still yet to be addressed. Recognizing the likelihood that commercial deep-sea mining will commence in the near future, policy options for managing the industry have been suggested in the literature (**Table 1**).

Ocean ecosystems are threatened by multiple stressors (for example, climate change, ocean acidification, de-oxygenation, pollution, including plastics, and poor fisheries management) and, accordingly, some have argued that the socio-economic benefits of seabed mining may not outweigh the potential impacts (Nash et al., 2017). Kim (2017) suggests that it is time to question the assumption that commercializing the Area will benefit all humankind and asks: "Is commercial exploitation of non-renewable resources from the ocean floor today really in the interest of humanity?".

Some argue that a coherent global policy that integrates science, policy and stakeholder dialog is necessary for seabed mining to be managed effectively (Boetius and Haeckel, 2018). Seabed mining can create transboundary issues – a sediment plume could span jurisdictions, such that coordinated management is essential. Some national governments sponsor mining development on their continental shelves (Miller et al., 2018). For example, in 2014, the State of Papua New Guinea secured US$ 113 million to fund a 15% share in the capital required to complete the development phase of mining activities in the Nautilus Minerals-operated Solwara 1 site[4,5].

Management of seabed mining as currently organized and envisaged is fragmented – because it is partly under ISA jurisdiction and partly under State control – and lacks transparency in many respects (Lallier and Maes, 2016; Durden et al., 2017, 2018). The Legal and Technical Commission of the ISA still holds its meetings in closed session, despite encouragement from the ISA Assembly to hold more open sessions and allow greater transparency[6]. Workshops to develop policy are primarily run by invitation only[7]. This contrasts with the relative openness of frameworks governing other aspects of maritime law, including the International Convention for the Prevention of Pollution from Ships (MARPOL) and the allied London Convention and Protocol (on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter), which have long traditions of active independent scrutiny by technical experts and observer organizations. Ardron et al. (2018) suggest that accountability could be improved by giving the public and non-government organizations (NGOs) greater access to information and that seabed mining management could be improved through more effective reporting of activities, quality assurance, compliance and an independent panel to review decisions. As well as opening the Legal and Technical Commission to observers, implementation of an environmental committee, as discussed in the ISA Council in March 2018, would assist in better integration of science with policy considerations[8]. A mechanism is still to be developed to assess environmental costs and detriment, social concerns and to integrate a dialog with stakeholders on the need for seabed mining. The ISA is currently developing exploitation regulations, which must ensure the effective protection of the marine environment from harmful effects (UNCLOS, article 145).

Mengerink et al. (2014) discuss the establishment of a fund, in lieu of conventional restoration, to cover research, monitoring and contingency for damage arising from human activities in the deep sea. Danovaro et al. (2017a) suggest the establishment of an agency under the United Nations (UN) to facilitate monitoring in the Area, but seabed monitoring is costly – Gramling (2014), for example, estimates that seafloor research can cost up to US$ 80,000 per day. Also, a regulatory body administering a common fund would need the power to appoint independent experts, fine contractors and, if necessary, halt detrimental mining activities (Halfar and Fujita, 2002). Management that incorporates a 'cessation clause' may incentivise contractors to minimize environmental harm but could not prevent it altogether. It is essential that there is clarity on who (contractors, the ISA or governments) is responsible for activities at every stage of mining (Ardron et al., 2018; Durden et al., 2018).

Environment

Growing demand for minerals has motivated a desire among some to exploit ocean resources. It is well known that seabed mining will cause irreversible damage to biodiversity on local scales and possibly wider areas depending on the type of mining (Jones et al., 2017; Van Dover et al., 2017; Miller et al., 2018). The impact of continuous and cumulative commercial-scale mining operations may generate interacting stressors that are very different from those associated with one single mining event (Van Dover, 2011) and well beyond the natural variations that the seabed has experienced to date. One approach to limit biodiversity loss in deep-sea ecosystems is to establish a coherent network of marine protected areas (MPAs) (Danovaro et al., 2017a; Roberts et al., 2017). Such networks can protect biodiversity from the impacts of deep-sea mining and other anthropogenic activities (Roberts et al., 2017). An added

[4]http://www.nautilusminerals.com/irm/PDF/1973_0/NautilusAnnouncesPreliminaryEconomicAssessmentforitsSolwara1Project

[5]http://www.nautilusminerals.com/IRM/PDF/1735/AnnualInformationFormforfiscalyearendedDecember312015

[6]ISA Document ISA/23/A/13, 18 August 2017. At https://www.isa.org.jm/document/isba23a13.

[7]See Earth Negotiations Bulletin report of the March 2018 Special Session in Congress, 5 March 2018, at http://enb.iisd.org/vol25/enb25153e.html.

[8]See Earth Negotiations Bulletin report of the March 2018 Special Session in Congress, 5 March 2018, at http://enb.iisd.org/vol25/enb25153e.html.

TABLE 1 | An overview of literature that discusses seabed mining policy, management, enforcement and alternatives and our evaluation, which sets out the pros and cons of these measures.

Potential improvement to policy	Pros	Cons	Reference
A new international monitoring initiative. Under the United Nations to facilitate monitoring, research and governance in the Area.	• Formation of a global Deep-Sea Ecosystem Monitoring Network for monitoring biodiversity with key explanatory variables. • Coordinated research and monitoring to inform governance. • May fit under the biodiversity beyond national jurisdiction agreement structure.	• Will not cover territorial seas or exclusive economic zone. • Potential impacts from outside the area would be monitored but not be addressed by policy.	Danovaro et al., 2017a
Develop coherent seabed protection policy. For example, the European Union banned benthic trawler fishing at >800 m due to slow recovery times of biota[a], but the EU Blue Growth Strategy (European Commission [EC], 2012) has identified seabed mining as a potential sector to provide jobs and economic growth. Commercial seabed mining may affect significant areas of the seabed. An estimated 1 million km[b] of seabed within the Area has been allocated for mineral exploration (Cuyvers et al., 2018).	• May contribute to joined up governance of seabed mining and bottom fishing. • Could promote global seafloor monitoring. • Would improve transparency and stakeholder dialog. • Would improve science–policy interface.	• Could be difficult to implement. • Would involve liaison between different stakeholders and international and national bodies, significant transparency and institutional reforms in the International Seabed Authority.	Boetius and Haeckel, 2018
Staged approach. A small number of mining sites with a perceived lower risk could be exploited to allow the development of mitigation technologies.	• Facilitates the collection of baseline data and impacts. • Facilitates the development of potential mitigation measures. • Public environmental impact assessments of testing and staging facilitates transparency, assessment of environmental effects.	• Could be perceived as a 'stepping stone' to full extraction particularly if no policy is in place to prevent further extraction. • Industry resistant due to capital cost of developing all equipment.	Niner et al., 2018
Reinterpret management of seabed mining in the context of United Nations Sustainable Development Goals (SDGs).	• Define benefit, in a context of SDGs and current global challenges.	• Would need to be within a transparent process, with appropriate institutional framework, open to all stakeholders, with non-government organization (NGO) participation.	Kim, 2017
The power to halt mining activities.	• Management can be adaptive as new scientific knowledge emerges.	• Monitoring and assessments would need to be undertaken/reviewed by independent experts with transparency. • Contracts must allow for cessation.	Halfar and Fujita, 2002
A disaster compensation fund.	• The 'polluter pays principle' could help to address knowledge gaps.	• May not lead to change in behavior of polluter if financial contribution is not large enough.	Mengerink et al., 2014
Effective environmental management framework.	• Enables implementation of the precautionary approach.	• Must comply with the United Nations Convention on the Law of the Sea and cover continental shelf applications. • External reviews are key.	Durden et al., 2017, 2018
Establish marine protected areas. To preserve species and ecosystems before mining activities take place.	• Protects endemic biodiversity from harm.	• Need to be adaptive, include areas within claims.	Van Dover et al., 2018
Improved transparency.	• Improved accountability. • Public will have greater access to information on impacts. • Periodic reviews that facilitate adaptive management. • Independent scientific evaluation, monitoring and reviews.	• None as such, though independent experts, including those within NGOs, would be needed. • Institutions need to adapt and evolve to encompass transparency and accountability.	Ardron et al., 2018
Enforced social cost–benefit analyses.	• Improved benefit sharing, including to local communities and indigenous peoples. • Set aside a designated fund for disasters and incidents. • Include reviews for cost–benefit analyses.	• Must include current baseline conditions, environmental externalities and address uncertainties.	Wakefield and Myers, 2016; World Bank, 2017

TABLE 1 | (Continued)

Potential improvement to policy	Pros	Cons	Reference
Formulate regulations to ensure effective protection of the marine environment.	• Effective protection of the marine environment is a high but essential goal. • Detailed definition of what constitutes 'serious harm' in relation to seabed mining is a necessary precondition.	• Would need to include estimates to quantify the effects of mining and gathering baseline data on which to inform policy prior to any commercial mining activity.	Levin et al., 2016
Fully inform the global community. Ensure complete understanding of the intra- and intergenerational impacts of marine mineral exploitation.	• Preservation of global resources for future generations. • Global distribution of benefits. • May prevent impacts from occurring without public consultation.	• Requires independent reporting, reviewing and full transparency.	Niner et al., 2018
Identify alternative materials. Fund research to find substitute metals for the burgeoning green technology sector.	• Maximizes global resources. • Avoids a reliance on one critical metal, such as silver that are used in photovoltaic cells.	• Does not address the issue of overconsumption of resources and planetary boundaries.	Grandell et al., 2016; Teske et al., 2016
Improved metals recycling infrastructure. Encourage a move toward a circular economy.	• Maximizes global resources and may avoid the need for seabed mining even under ambitious renewable energy scenarios.	• Will require initial planning and investment in recycling infrastructure. • Will require a significant shift to replace fossil fuel energy sources, including technologies and infrastructure built around combustion engines.	Teske et al., 2016

[a]*The EU trawler regulation is here: http://data.consilium.europa.eu/doc/document/ST-11625-2016-REV-1/en.* [b]*http://www.nautilusminerals.com/irm/PDF/1989_0/NautilusMineralsSeafloorProductionVesselLaunched.*

advantage of MPA networks is that the creation of management plans can help biologists to gather baseline data on deep-sea ecosystems (Dunn et al., 2018).

Seabed mining could be extremely costly given that the ocean provides significant services (Worm et al., 2006; Palumbi et al., 2009; Barbier, 2017; Le et al., 2017). Marine ecosystem services include breeding grounds and nursery habitats for fisheries, pharmaceutical and genetic resources, climate regulation and nutrient cycling (Le et al., 2017). Mitigating biodiversity loss and large-scale restoration of deep-sea ecosystems after mining is likely to remain expensive and technologically difficult, or impossible (Van Dover et al., 2014, 2017; Niner et al., 2018). Studies documenting the recovery of terrestrial and marine ecosystems show that even if restoration is part of the wider management of seabed mining, it is highly unlikely that biodiversity will fully recover (Jones et al., 2018).

Currently, environmental impact assessments (EIAs) do not always take into account the dynamic nature or interconnectivity of marine ecosystems, or that an ecosystem may be subject to multiple stressors. Conducting an EIA for deep seabed mining in the Area is challenging because of the environmental conditions and uncertainties involved, which include a lack of environmental data at all spatial and temporal scales and the fact that mining technologies remain under development (Durden et al., 2018). Concerns have been raised that data collected by contractors vary in quality and consistency (International Seabed Authority [ISA], 2017). If EIAs are to be used to predict the impacts of the proposed mining activity, standardization of their implementation and strict checks on their quality would need to be addressed with considerable urgency.

Durden et al. (2018) consider that EIA frameworks should guide contractors on how to provide data during mining exploration, but the frameworks do not specify how such data would link to future exploitation. Durden et al. (2018) stress that EIA data must influence decision making at the policy level.

A precautionary approach, as envisaged by Durden et al. (2017), would incorporate routine reviews to prevent – rather than assess the likelihood of – harm. Levin et al. (2016) suggest that uncertainties such as lack of baseline ecological data warrant the use of the precautionary approach. The precautionary approach aims to ensure a high level of environmental protection through the use of smart, risk-averting decisions, but the term can be interpreted in different ways by different stakeholders.

Van Dover et al. (2017) suggest that equipment design, such as shrouds placed around cutting machines to limit sediment plumes, might mitigate some environmental impacts. However, the efficacy of such steps has not yet been demonstrated. Niner et al. (2018) argue that mitigation measures should consider spatial planning, including the distribution of habitats, species ranges and connectivity, and the location and extent of proposed mining. Many aspects of deep-sea species biology are unknown – it is impossible to predict genetic or demographic connectivity for species that have yet to be described. Mining could lead to widespread habitat loss and to species extinction.

Marine ecosystems are under increasing pressure from climate change, ocean acidification, oil and gas extraction, fishing, marine litter and shipping (United Nations [UN], 2016). In future, should commercial mining take place, it is plausible that exploitation could occur simultaneously in multiple adjacent locations – whether on vents, on seamounts or on nodule fields. Forecasting and evaluating the effects of deep seabed mining will involve quantifying the cumulative and interacting effects of mining combined with other stressors (Levin et al., 2016; Kroeker et al., 2017). A strategic environmental assessment could be a first step toward assessing the impact of multiple anthropogenic activities in the ocean (Rogers, 2018). An audit of baseline data and an assessment of the health status of the deep-sea ecosystems will help to predict the resilience of biota to cumulative human pressures. In response to such concerns, Niner et al. (2018) discuss the principle of 'no net loss'. No net loss is part of a mitigation hierarchy that is applied to activities that impact terrestrial ecosystems. Briefly described, the mitigation hierarchy is: avoid impacts -> minimize impacts -> remediate impacts -> biodiversity offsetting (one ecosystem is substituted for another). The authors conclude that avoidance and minimizing impacts from seabed mining are the only viable means of reducing biodiversity loss (Niner et al., 2018). Boetius and Haeckel (2018) go further and state that managing the risks of commercial seabed mining is not possible, from either a financial or ecological perspective.

Niner et al. (2018) suggest a staged approach to seabed mining in which a small number of sites are exploited to facilitate the development of mitigation technologies. Intensive research of mined and pristine areas could allow stakeholders to amass detailed knowledge of ecosystems and the impacts of mining. The authors stipulate that biodiversity loss caused by mining must be communicated to the global community because impacts will be inevitable, permanent and could otherwise be invisible to the public or decision-makers. If such a staged approach were to be adopted, it would require full monitoring and reporting by companies and robust evaluation (Durden et al., 2018). A staged approach could even be seen as a stepping-stone to full mineral extraction if no legal instrument is in place to enable mining to be halted should the need arise. Another issue is that industry is likely to resist staging because of the high capital costs involved in developing mining equipment and the need to recoup the investment (Durden et al., 2018).

Community

The United Nations Convention on the Law of the Sea, as amended by the 1994 Implementing Agreement, does not prescribe the financial mechanism through which benefits of seafloor mineral exploitation could be redistributed – it rather describes benefits as needing to be 'equitable' (Article 160 UNCLOS; Bourrel et al., 2016). This raises the question of intergenerational equity as well as broader questions such as access to and sharing of marine genetic resources. Given the potential scale and irreversibility of impacts from seabed mining, mechanisms must be found with urgency to address fundamental questions regarding the justification for, and acceptability of, extraction of seabed minerals (Lallier and Maes, 2016; Van Dover et al., 2017; Durden et al., 2018). The physical, ecological and societal implications of decisions to allow seabed mining are wide ranging and complex (**Box 2**). Key issues to be addressed, and which justify broad societal engagement in guiding policy decisions, include:

(1) Seabed mining will damage the marine environment for many centuries (Van Dover et al., 2017);

(2) Mining activities could affect fish stocks (Levin et al., 2016);

(3) No liability regime exists and, if established, would warrant the establishment of a fund to cover gaps in liability coverage, such as impecuniosity of operators;

(4) A system to distribute mining benefits to current and future generations of the global community has not yet been defined (Kim, 2017);

(5) Advocating the continued exploitation of Earth's resources is likely to reinforce unsustainable patterns of consumption;

(6) Seabed mining could affect carbon sequestration in sediments (Nath et al., 2012; German et al., 2015); and

(7) Potential marine genetic resources could be degraded before they have been evaluated (Armstrong et al., 2012).

Accidents and incidents caused by seabed mining have been described as 'low probability, high risk' (Wakefield and Myers, 2016). As was evidenced by the 2010 BP Deepwater Horizon disaster, marine accidents and incidents can include unanticipated incidents with far reaching effects, especially if they occur offshore at extreme depth. Such events can involve not only financial losses but grave social and environmental

BOX 2 | Conflicts of interest.

Mineral extraction from the seabed will unquestionably be disruptive. Management and regulation of seabed mining will need to take into consideration the many stakeholders – each of whom will have vastly different interests – that may be impacted by activity from extractive industries. Examples of potential conflicts between seabed mining and other stakeholders include:

- Subsistence and commercial fisheries. Could be affected by noise, light and sediment plumes from mining vessels and machinery (Miller et al., 2018).
- Biological resources. Potentially valuable as sources of novel pharmaceuticals. Advances in bioinformatics and genetic sequencing have identified potential therapeutic applications. Rights and access to marine genetic resources and marine scientific research are governed under two legally binding instruments: United Nations Convention on the Law of the Sea (UNCLOS) and the Nagoya Protocol, which apply within the national jurisdiction of coastal states (Lallier et al., 2014). Access to genetic resources in the Area is not currently subject to regulation (Vierros et al., 2016).
- Carbon budgeting. Nath et al. (2012) found increased turnover of sedimentary carbon in a small-scale disturbance experiment; effects that would be multiplied many-fold by commercial-scale mining activity. The findings of German et al. (2015) suggest that hydrothermal vents could be globally important ecosystems for delivering organic carbon to deep-sea sediments. Disturbance of processes that affect carbon burial in the sediments could have far-reaching effects on carbon sequestration that in turn is connected to climate regulation (Le et al., 2017), though these are likely to remain difficult to document in quantitative terms.
- Tourism. For example, the threat of offshore hydrocarbon extraction in the territorial waters of Portugal initiated a campaign by the tourist and fishing industries (http://palp.pt/index.php/en/). Álvarez-Albelo (2012) reports a similar 'tourism versus extractive industry' controversy in Spain's territorial waters. Folkersen et al. (2018) suggest that deep sea mining off the coast of Fiji could reduce tourism revenue.

costs. A social cost–benefit analysis could assess a proposed mining activity in relation to the environment, economy and local and global communities (Wakefield and Myers, 2016; World Bank, 2017). Such processes would need to include environmental externalities and regular re-appraisal to incorporate relevant technological, cultural and environmental changes and a mechanism is needed to enforce assessed benefits. The high level of uncertainty associated with seabed mining compounds the difficulties in a cost–benefit analysis (World Bank, 2017).

Economic benefits gained by local communities from commercial mining on continental shelves are likely only to be realized as employment opportunities and through local redistribution of royalties. Economic evaluation must also take into account economic costs, such as lost tourism or fishing opportunities, and environmental costs, which are notoriously difficult to quantify.

The evaluation of a seabed mining proposal needs full transparency, together with effective quantification and communication of the manifold impacts of mining, the benefits and the justification for mining virgin materials. For this, the ISA needs to implement full modern transparency procedures, hold meetings of the Legal and Technical Commission in public, initiate full public comment and review procedures in the exploitation regulations being formulated, with respect to all matters, and issue open invitations to workshops developing policy and procedures. Communication is key because the consequences of biodiversity loss are so great, and decisions relating to exploitation of seabed minerals cannot be left to those with predominantly economic interests. Equally important is to ensure that the global community understands that no financial provision to clean up or mitigate environmental damage (accidental or otherwise) will compensate for the loss of ecosystems that may take millennia to recover (Niner et al., 2018).

Communities that rely on fish stocks for subsistence could be particularly vulnerable to the impacts of seabed mining. Mining could take place offshore from remote islands such as small-island states of the Pacific or along mid-ocean ridges. Some impacts, particularly sediment plume dispersal, could cross jurisdictional boundaries into coastal waters. Because no commercial-scale seabed mining has yet taken place, a mechanistic description of the extent to which local communities will be affected by seabed mining is difficult to provide. It is imperative that these communities understand the nature of the proposed activities and the ways in which their livelihoods could change so that they are empowered to make informed representations. It is plausible that local people may feel that they are powerless to prevent mining if the economic drive to extract minerals is sufficiently high.

ALTERNATIVES TO SEABED MINING

The global population is set to reach 8.6 billion by 2030[9]. This trend, along with increasing industrialization and growth in household incomes in many parts of the world, can lead to increased demand for resources (Gordon et al., 2006; Izatt et al., 2014). Current levels of global resource use are predicted to more than double by 2050, much of which will be consumed by emerging economies to build housing and infrastructure (Krausmann et al., 2017). The current level of resource use is unsustainable and has prompted some researchers to call for global change in patterns of consumption (of metals but also of other commodities such as plastics) (Kim, 2017; Boetius and Haeckel, 2018; O'Neill et al., 2018).

The mining industry claims that seabed mining will ensure the supply of metals for use in efficient, clean technologies, including reports that exploiting certain deep-sea mineral deposits will "reduce the footprint of mineral extraction" (Halfar and Fujita, 2002; The Economist, 2018). Other reports find that there is no need to turn to deep seabed mining (Teske et al., 2016) Relying on existing terrestrial mines, say some advocates, will mean continued social and environmental problems. The social and environmental impacts of terrestrial mining are well publicized and include construction of infrastructure, impacts from the disposal of mine tailings and emissions that can lead to atmospheric pollution. Others note, however, that seabed mining will cause benthic disturbance, plumes and noise, the significance of which is indisputable (Kim, 2017). Moreover, Halfar and Fujita (2002) argue that the environmental effects

[9] 2017 Revision of World Population Prospects. Available at: https://esa.un.org/unpd/wpp/

BOX 3 | Overconsumption and the need for a circular economy.

Concerns have been raised that no country can meet basic human needs at a level of resource use that is globally sustainable (O'Neill et al., 2018). Reducing overall consumption in tandem with implementing a circular economy will make a significant impact on fulfilling demands to manufacture new technology and alleviate waste. Improved recycling technology and careful product design will help to maximize resources (Gordon et al., 2006; Grandell et al., 2016).

Successful implementation of a circular economy will involve changing patterns of consumption and will represent a huge, but not insurmountable, challenge for societies around the globe. A combination of measures such as policy, pricing and a shift in demand could allow economic growth while simultaneously slowing global material use (Krausmann et al., 2017). For example, policy could require companies to manufacture technologies that are fully recyclable at end-of-life, extending product lifespans and eliminating built-in obsolescence. Other changes in behavior could be incentivized by improvements to public transport, including bike lanes, car sharing, shared use of white goods and less frequent upgrades of personal technology.

Policy measures could help to encourage metals recycling and reuse on a global level. The volume of electronic waste (e-waste) is increasing but recycling certain components can be technically and logistically challenging (Tansel, 2017). Gordon et al. (2006) report that metals have the potential for "almost infinite recovery and reuse", but recycling can be challenging if it involves extracting metals that have previously been disposed of in landfill. Policy could be used to guide collection, tracking, safe handling, recovery and onward sale of reusable materials. Grandell et al. (2016) report that the metals market is dominated by input from the mining industry. As metals become scarce, prices will rise and, in turn, recycling infrastructure will develop. Grandell et al. (2016) recommend research to find substitute metals to use in green technologies so that reliance widens from using only a few crucial metals.

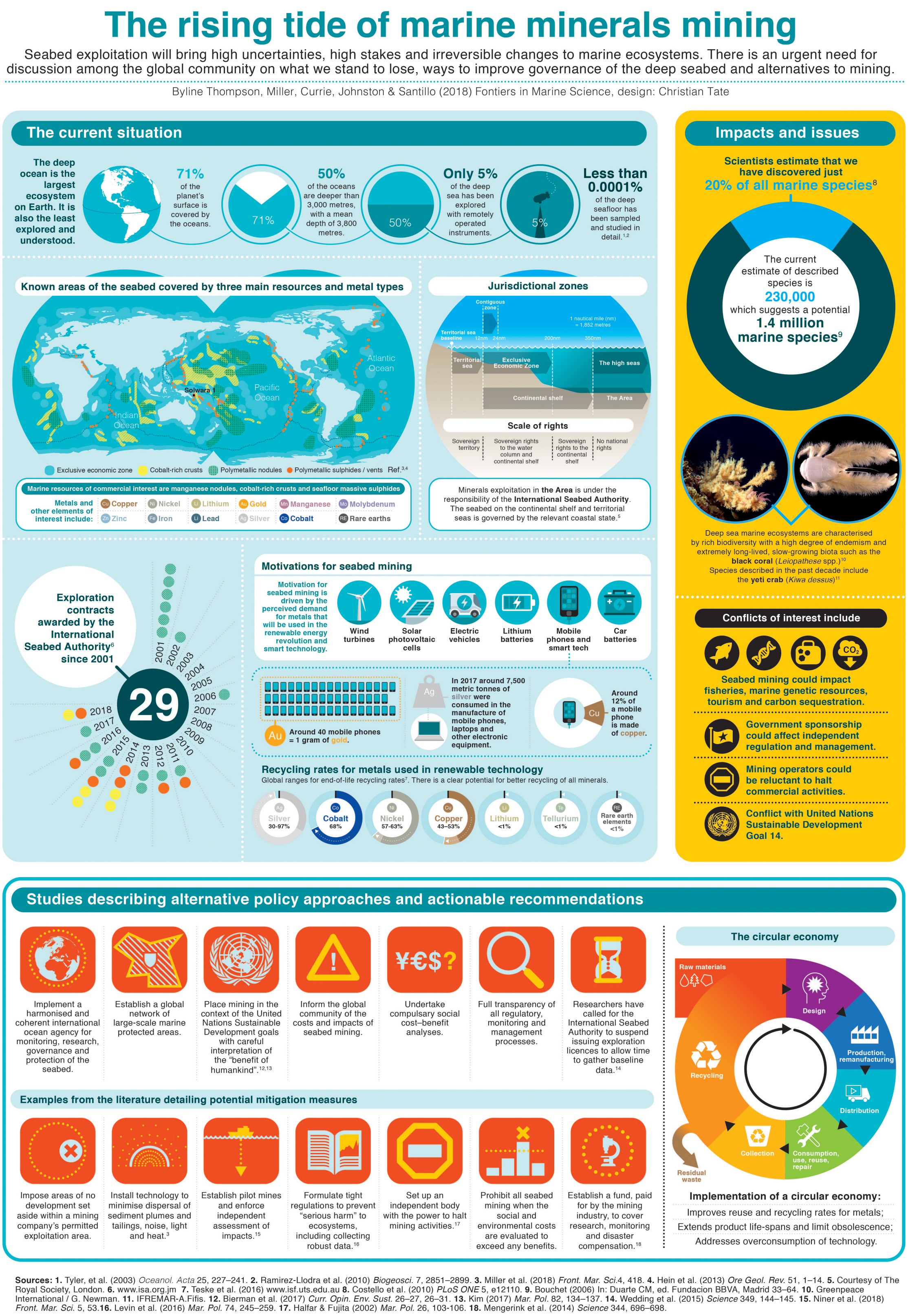

FIGURE 1 | The rising tide of marine minerals mining. An infographic that outlines the current situation and impacts of seabed mining including potential mitigation measures and actionable recommendations.

of deep-sea mining could have a wider impact than mining on land.

One solution suggested by Ghisellini et al. (2016) is to implement a circular economy, which may yield significant benefits through metals reuse (**Box 3**). Bleischwitz et al. (2018) analyzed consumption patterns of copper, aluminum, cement and steel projected over one century and suggested that future demand for resources could be lower than expected as countries reach a stage at which consumption reaches saturation. Boetius and Haeckel (2018) outline the hazards of seabed mining and call for an evaluation of the fluxes and fates of metal use, which could better inform decisions regarding mineral exploitation. Implementation of a circular economy would be complex because it involves a multitude of other processes such as waste management, reduced use of resources and global behavior change, though such challenges should not preclude its consideration and adoption. Broader integration of environmental costs and risks, social and economic drivers, science and stakeholder dialog as well as better inter-sectoral and regional coordination is essential.

ACTIONABLE RECOMMENDATIONS

Our policy brief has led us to formulate the following guidance, arranged in five broad themes, that would protect marine ecosystems from harm and could help to improve governance of the deep seabed in relation to mining (see also **Figure 1**).

1. Sustainability: Full implementation of a circular economy by improving reuse and recycling rates, enhancing the design of smart technology, extending product lifespans, limiting obsolescence and discouraging overconsumption.
2. Monitoring: Governance by the ISA is fragmented and currently EIAs are not standardized or independently verified. Implement advanced baseline data collection, establish robust monitoring protocols and research of deep-sea ecosystems through a coherent international ocean agency.
3. Protection: Establish a coherent network of MPAs.
4. Transparency: Fully inform the global community, including all indigenous groups and small-island states, of the costs and benefits of the proposed activity according to the UNCLOS stipulation that activities in the deep sea must be carried out for "the benefit of mankind". Achieve community engagement through compulsory social cost–benefit analyses together with the establishment of full transparency of all regulatory, monitoring and management processes.
5. Legislation: In the event that seabed mining proceeds it is imperative that the ISA or other regulatory body has the power to halt mining based on independent assessments. Technology to minimize impacts and strict regulations to prevent serious harm to ecosystems must be enforced by the regulatory body and independently verified. Appropriate policy and funding would be required to ensure that any legislated powers are enforced.

CONCLUSION

Seabed mining will cause irreparable damage to marine ecosystems. Global communities must fully understand the implications of mining because large parts of the seabed are legally the 'common heritage of mankind' (Bourrel et al., 2016; Van Dover et al., 2017; Boetius and Haeckel, 2018; Jones et al., 2018). At present, regulation of activities that impact on the seabed, including proposed mineral extraction, are set to be regulated differently depending on whether they are in the Area (under ISA rules) or on continental shelf areas (under a diversity of national jurisdictions). If seabed mining becomes a reality, a globally harmonized system for protecting the seabed is needed (Wedding et al., 2015). In common with many of the instruments applicable to their overlying waters, a harmonized system would need to take into account stressors such as ocean acidification, climate change and pollution. Such an approach could help to avoid fragmented, inconsistent approaches to regulating activities in different regions, though some level of systematic and permanent damage to ecosystems would be unavoidable. When developing the proposed international legally binding instrument on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction, consideration will also need to be given to ensure at least equivalent levels of protection within national jurisdictions (United Nations [UN], 2017). Conflicts could arise if a sovereign State does not agree with a harmonized system of ocean governance.

Addressing biodiversity threats from seabed mining is paramount. Establishing MPAs before exploration and exploitation is a priority and detailed monitoring is key (Halfar and Fujita, 2002; Van Dover et al., 2017, 2018). Wedding et al. (2015) support the application of the precautionary principle in relation to establishing MPAs in deep-sea mining regions. Lessons learned from the planning process relating to exploration claims within the Clarion Clipperton Zone (CCZ) in the Pacific Ocean indicate that existing and emerging claims reduced the effectiveness of proposed science-based MPA networks. Wedding et al. (2015) suggest that all exploration contracts are suspended and no exploitation contracts are issued until MPA networks are fully implemented. Giving marine scientists the opportunity to fully survey an area of the seabed and overlying waters before any permits are issued could help to protect fragile biota if the survey data are used to formulate policy. In the absence of robust baseline environmental data, contractors may otherwise simply designate no-mine areas, or preservation reference zones, in regions of their contract area that are devoid of nodules and, therefore of no financial interest (Gjerde et al., 2016; Vanreusel et al., 2016) rather than on the basis of informed conservation objectives. Improvements to the current ISA could include full transparency and independent scientific reviews at all stages by observers from NGOs or institutions (Ardron et al., 2018).

The United Nations' Sustainable Development Goals[10] signify an obligation to protect the environment and ensure access to resources for current and future generations. Current levels

[10]http://www.un.org/sustainabledevelopment/development-agenda/

of consumption are unsustainable (Kim, 2017; O'Neill et al., 2018). Part of the solution – in the supply of raw materials for technologies – is to move toward a circular economy (European Commission [EC], 2017). An optimized circular economy will entail a paradigm shift from mining primary resources to adopting radical behavioral changes best described as 'dematerialization' (Kim, 2017; Boetius and Haeckel, 2018). Future challenges associated with e-waste recycling include lack of awareness and of motivation, although arguably both could be overcome with investment, education and policy instruments (Izatt et al., 2014; Tansel, 2017).

Demand is increasing for minerals with which to manufacture smart technologies and green energy, particularly in light of the Paris Agreement and the transition toward a low-carbon society (European Commission [EC], 2011; Alonso et al., 2012; Grandell et al., 2016; Ali et al., 2017). In 2011, 97% of the world's production of rare earth elements involved China, prompting the industry to look for mineral reserves elsewhere, including the deep sea, to safeguard supply (Kato et al., 2011). However, Teske et al. (2016) claim that even with ambitious future energy scenarios metal demand associated with renewable technologies will not require seabed mining. The need for minerals is apparent but the focus must be on research and development to establish effective recycling programs and find alternative technologies that reduce, or eliminate, the use of supply constrained metals.

Advances in science and technology present myriad opportunities – and drawbacks – for humanity. As a global civilization, it is necessary to evaluate the benefits and costs of anthropogenic activities in a world in which resources are finite and the environmental costs of previous actions present global challenges for generations to come.

AUTHOR CONTRIBUTIONS

KT and KM contributed equally to researching, writing, and conceiving the manuscript. DC, DS, and PJ edited the manuscript. DS and PJ funded the work.

FUNDING

The preparation of this manuscript was funded by Greenpeace to provide independent scientific advice and analytic services to that non-governmental organization.

REFERENCES

Ali, S., Giurco, D., Arndt, N., Nickless, E., and Brown, G., Demetriades, A. et al. (2017). Mineral supply for sustainable development requires resource governance. *Nature* 543, 367–372. doi: 10.1038/nature21359

Alonso, E., Sherman, A., Wallington, T., Everson, M., and Field, F. et al. (2012). Evaluating rare earth element availability: a case with revolutionary demand from clean technologies. *Environ. Sci. Technol.* 46, 3406–3414. doi: 10.1021/es203518d

Álvarez-Albelo, C. D. (2017). Potential fiscal revenues from hydrocarbon extraction for the tourism region of the canary islands. *Soc. Study* 7, 235–245. doi: 10.17265/2159-5526/2017.05.001

Ardron, J., Ruhl, H., and Jones, D. (2018). Incorporating transparency into the governance of deep-seabed mining in the area beyond national jurisdiction. *Mar. Policy* 89, 58–66. doi: 10.1016/j.marpol.2017.11.021

Armstrong, C., Foley, N., Tinch, R., and van den Hove, S. (2012). Services from the deep: steps towards valuation of deep sea goods and services. *Ecosyst. Serv.* 2, 2–13. doi: 10.1016/j.ecoser.2012.07.001

Barbier, E. B. (2017). Marine ecosystem services. *Curr. Biol.* 27, R507-R510. doi: 10.1016/j.cub.2017.03.020

Bleischwitz, R., Nechifor, V., Winning, M., Huang, B., and Geng, Y. (2018). Extrapolation or saturation: revisiting growth patterns, development stages and decoupling. *Glob. Environ. Chang.* 48, 86–96. doi: 10.1016/j.envint.2016.10.002

Boetius, A., and Haeckel, L. (2018). Mind the seafloor. *Science* 359, 34–36. doi: 10.1126/science.aap7301

Bourrel, M., Thiele, T., and Currie, D. (2016). The common heritage of mankind as a means to assess and advance equity in deep sea mining. *Mar. Policy* 95, 311-316 doi: 10.1016/j.marpol.2016.07.017

Carreiro-Silva, M., Andrews, A., Braga-Henriques, A., de Matos, V., Porteiro, F. M., and Santos, R. S. (2013). Variability and growth of long-lived black coral Leiopathes sp. from the Azores. *Mar. Ecol. Prog. Ser.* 473, 189–199. doi: 10.3354/meps10052

Cuyvers, L., Berry, W., Gjerde, K., Thiele, T., and Wilhem, C. (2018). *Deep seabed mining: a rising environmental challenge. Gland,* Switzerland: IUCN and Gallifrey Foundation. doi: 10.2305/IUCN.CH.2018.16.en

Danovaro, R., Aguzzi, J., Fanelli, E., Billet, D., Gjerde, K., Jamieson, A., et al. (2017a). An ecosystem-based deep-ocean strategy. *Science* 355, 452–454. doi: 10.1126/science.aah7178

Danovaro, R., Corinaldesi, C., Dell'Anno, A., and Snelgrove, P. V. R. (2017b). The deep-sea under global change. *Curr. Biol.* 27, R461-R465. doi: 10.1016/j.cub.2017.02.046

Dunn, D. C., Van Dover, C. L., Etter, R. J., Smith, C. R., Levin, L. A., Morato, T., et al. (2018). A strategy for the conservation of biodiversity on mid-ocean ridges from deep-sea mining. *Sci. Adv.* 4:eaar4313. doi: 10.1126/sciadv.aar4313

Durden, J. M., Lallier, L. E., Murphy, K., Jaeckel, A., Gjerde, K., and Jones, D. O. B. (2018). Environmental impact assessment process for deep-sea mining in 'the Area'. *Mar. Policy* 87, 194–202. doi: 10.1016/j.marpol.2017.10.013

Durden, J. M., Murphy, K., Jaeckel, A., Van Dover, C. L., Christiansen, S., Gjerde, K., et al. (2017). A procedural framework for robust environmental management of deep-sea mining projects using a conceptual model. *Mar. Policy* 84, 193–201. doi: 10.1016/j.marpol.2017.07.002

European Commission [EC]. (2011). *European Commission: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A Roadmap for Moving to a Competitive Low Carbon Economy in 2050*. Available At: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52011DC0112

European Commission [EC]. (2012). *European Commission: European Commission: Blue Growth: Opportunities for Marine and Maritime Sustainable Growth*. Brussels: European Commission

European Commission [EC]. (2017). *European Commission: Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the Implementation of the Circular Economy Action Plan*. Available at: http://ec.europa.eu/environment/circular-economy/implementation_report.pdf

Folkersen, M. V., Fleming, C. M., and Hasan, S. (2018). Deep sea mining's future effects on Fiji's tourism industry: a contingent behaviour study. *Mar. Policy* 96, 81–89. doi: 10.1016/j.marpol.2018.08.001

German, C., Legendre, L., Sander, S., Niquil, N., Luther III, G., Bharati, L., et al. (2015). Hydrothermal Fe cycling and deep ocean organic carbon scavenging: model-based evidence for significant POC supply to seafloor sediments. *Earth Planet. Sci. Lett.* 419, 143–153. doi: 10.1016/j.epsl.2015.03.012

Ghisellini, P., Cialani, C., and Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *J. Clean. Prod.* 114, 11–32. doi: 10.1016/j.jclepro.2015.09.007

Gjerde, K. M., Weaver, P., Billett, D., Paterson, G., Colaco, A., Dale, A. et al. (2016). *Report on the Implications of MIDAS Results for Policy Makers with*

Recommendations for Future Regulations to be Adopted by the EU and the ISA. Managing Impacts of Deep Sea Resource Exploitation. Available at: http://www.eu-midas.net/sites/default/files/deliverables/D9.6_FINAL_lowres.pdf [Accessed September 18, 2018].

Glasby, G. (2000). Lessons learned from deep-sea mining. *Science* 289, 551-553. doi: 10.1126/science.289.5479.551

Gollner, S., Kaiser, S., Menzel, L., Jones, D. O. B., Brown, A., Mestre, N. C., et al. (2017). Resilience of benthic deep-sea fauna to mining activities. *Mar. Environ. Res.* 129, 76–101. doi: 10.1016/j.marenvres.2017.04.010.

Gordon, R. B., Bertram, M., and Graedel, T. E. (2006). Metal stocks and sustainability. *Proc. Natl. Acad. Sci. U.S.A.* 107, 1209–1214. doi: 10.1073/pnas.0509498103

Gramling, C. (2014). Seafloor mining plan advances, worrying critics. *Science* 344:463. doi: 10.1126/science.344.6183.463

Grandell, L., Lhtilä, A., Kivinen, M., Koljonen, T., Kihlman, S., and Lauri, L. (2016). Role of critical metals in the future markets of clean energy technologies. *Renew. Energ.* 95, 53–62. doi: 10.1016/j.renene.2016.03.102

Halbach, P., Marchig, V., and Scherhag, C. (1980). Regional variations in Mn, Ni, Cu, and Co of ferromanganese nodules from a basin in the Southeast Pacific. *Mar. Geol.* 38, M1-M9. doi: 10.1016/0025-3227(80)90001-8

Halfar, J., and Fujita, R. M. (2002). Precautionary management of deep-sea mining. *Mar. Policy* 26, 103–106. doi: 10.1016/S0308-597X(01)00041-0

International Seabed Authority [ISA]. (2017). *International Seabed Authority: Final Report on the Periodic Review of the International Seabed Authority Pursuant to Article 154 of the United Nations Convention on the Law of the Sea*. Available at: https://www.isa.org.jm/sites/default/files/files/documents/isba-23a-3_1.pdf [Accessed October 2, 2018].

Izatt, R., Izatt, S., Bruening, R., Izatt, N., and Moyer, B. (2014). Challenges to achievement of metal sustainability in our high-tech society. *Chem. Soc. Rev.* 43, 2451–2475. doi: 10.1039/c3cs60440c

Jones, D. O. B., Kaiser, S., Sweetman, A. K., Smith, C. R., Menot, L., Vink, A., et al. (2017). Biological responses to disturbance from simulated deep-sea polymetallic nodule mining. *PLoS One* 12:e0171750. doi: 10.1371/journal.pone.0171750

Jones, H. P., Jones, P. C., Barbier, E. B., Blackburn, R. C., Rey Benayas, J. M., Holl, K. D., et al. (2018). Restoration and repair of Earth's damaged ecosystems. *Proc. R. Soc. B* 285:2017257. doi: 10.1098/rspb.2017.2577

Kato, Y., Fujinaga, K., Nakamura, K., Takaya, Y., Kitamura, K., Ohta, J., et al. (2011). Deep-sea mud in the pacific ocean as a potential resource for rare-earth elements. *Nat. Geosci.* 4, 535–539. doi: 10.1038/ngeo1185

Kim, R. (2017). Should deep seabed mining be allowed? *Mar. Policy* 82, 134–137. doi: 10.1016/j.marpol.2017.05.010

Krausmann, F., Schandl, H., Eisenmenger, N., Giljum, S., and Jackson, T. (2017). Material flow accounting: measuring global material use for sustainable development. *Annu. Rev. Environ. Resour.* 42, 647-675. doi: 10.1146/annurev-environ-102016-060726

Kroeker, K., Kordas, R., and Harley, C. (2017). Embracing interactions in ocean acidification research: confronting multiple stressor scenarios and context dependence. *Biol. Lett.* 13:20160802. doi: 10.1098/rsbl.2016.0802

Lallier, L. E., and Maes, F. (2016). Environmental impact assessment procedure for deep seabed mining in the area: independent expert review and public participation. *Mar. Policy* 70, 212–219. doi: 10.1016/j.marpol.2016.03.007

Lallier, L. E., McMeel, O., Greiber, T., Vanagt, T., Dobson, A. D. W., and Jaspars, M. (2014). Access to and use of marine genetic resources: understanding the legal framework. *Nat. Prod. Rep.* 31, 612–616. doi: 10.1039/C3NP70123A

Le, J. T., Levin, L. A., and Carson, R. T. (2017). Incorporating ecosystem services into environmental management of deep-seabed mining. *Deep Sea Res. Part 2 Top. Stud. Oceanogr*. 137, 486– 503. doi: 10.1016/j.dsr2.2016.08.007

Levin, L. A., Mengerink, K., Gjerde, K. M., Rowden, A. A., Van Dover, C. L., Clark, M. R., et al. (2016). Defining "serious harm" to the marine environment in the context of deep-seabed mining. *Mar. Policy* 74, 245–259. doi: 10.1016/j.marpol.2016.09.032

Mengerink, K. J., Van Dover, C. L., Ardron, J., Baker, M., Escobar-Briones, A., Gjerde, K., et al. (2014). A call for deep-ocean stewardship. *Science* 344, 696–698. doi: 10.1126/science.1251458

MIDAS (2016). *Managing Impacts of Deep-Sea Resource Exploitation*. Available at: https://www.eu-midas.net/

Miller, K. A., Thompson, K. F., Johnston, P., and Santillo, D. (2018). An overview of seabed mining including the current state of development, environmental impacts, andknowledge gaps. *Front. Mar. Sci.* 4:418. doi: 10.3389/fmars.2017.00418

Montero-Serra, I., Linares, C., Doak, D. F., Ledoux, J. B., and Garrabou, J. (2018). Strong linkages between depth, longevity and demographic stability across marine sessile species. *Proc. R. Soc. B* 285:20172688. doi: 10.1098/rspb.2017.2688

Nash, K., Cvitanovic, C., Fulton, E., Halpern, B., Milner-Gulland, E. J., and Watson, R. A. et al. (2017). Planetary boundaries for a blue planet. *Nat. Ecol. Evol.* 1, 1625–1634. doi: 10.1038/s41559-017-0319-z

Nath, B. N., Khadge, N. H., and Nabar, S. (2012). Monitoring the sedimentary carbon in an artificially disturbed deep-sea sedimentary environment. *Environ. Monit. Assess.* 184:2829. doi: 10.1007/s10661-011-2154-z

Niner, H. J., Ardron, J. A., Escobar, E. G., Gianni, M., Jaeckel, A., Jones, D. O. B., et al. (2018). Deep-sea mining with no net loss of biodiversity – an impossible aim. *Front. Mar. Sci.* 5:53. doi: 10.3389/fmars.2018.00053

O'Neill, D. W., Fanning, A. L., Lamb, W. F., and Steinberger, J. K. (2018). A good life for all within planetary boundaries. *Nat. Sustain.* 1, 88–95. doi: 10.1038/s41893-018-0021-4

Palumbi, S., Sandifer, P. A., Allan, J. D., Beck, M. W., Fautin, D. G., Fogarty, M. J., et al. (2009). Managing for ocean biodiversity to sustain marine ecosystem services. *Front. Ecol. Environ.* 7, 204–211. doi: 10.1890/070135

Roberts, C. M., O'Leary, B. C., McCauley, D. J., Cury, P. M., Duarte, C. M., Lubchenco, J., et al. (2017). Marine reserves can mitigate and promote adaptation to climate change. *Proc. Nat. Acad. Sci. U.S.A.* 114, 6167–6175. doi: 10.1073/pnas.1701262114

Rogers, A. (2018). "The biology of seamounts: 25 years on." in *Advances in Marine Biology*, ed. C. Sheppard (Academic Press, London), 137–224. doi: 10.1016/BS.AMB.2018.06.001

Tansel, B. (2017). From electronic consumer products to e-wastes: global outlook, waste quantities, recycling challenges. *Environ. Int.* 98, 35–45. doi: 10.1016/j.envint.2016.10.002

Teske, S., Florin, N., Dominish, E., and Giurco, D. (2016). *Renewable Energy and Deep Sea Mining: Supply, Demand and Scenarios. Report Prepared by ISF for J. M. Kaplan Fund, Oceans 5, and Synchronicity Earth*. Australia: Institute for Sustainable Futures.

The Economist (2018). Technology quarterly special (March 10). undersea mining: race to the bottom. *Economist* 426, TQ5-TQ6.

United Nations Convention on the Law of the Sea [UNCLOS] (1982). *Montego Bay, 10 December 1982, in Force 6 November 1994, 21 ILM 1261–1354, 1982, Article 140*. Montego Bay: United Nations Convention on the Law of the Sea.

United Nations [UN] (2016). *United Nations: A Regular Process for Global Reporting and Assessment of the State of the Marine Environment, Including Socio-economic Aspects (Regular process). First global Integrated Marine Assessment (First World Ocean Assessment)*. Available at: http://www.un.org/depts/los/global_reporting/WOA_RegProcess.htm [Accessed September 16, 2018].

United Nations [UN] (2017). *General Assembly Resolution 72/249, International Legally Binding Instrument Under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable use of Marine Biological Diversity of Areas Beyond National Jurisdiction*. Montego Bay: United Nations

Van Dover, C. L. (2011). Tightening regulations on deep-sea mining. *Nature* 470, 31–33. doi: 10.1038/470031a

Van Dover, C. L., Ardron, J. A., Escobar, E., Gianni, M., Gjerde, K. M., Jaeckel, A., et al. (2017). Biodiversity loss from deep-sea mining. *Nat. Geosci.* 10, 464–465. doi: 10.1038/ngeo2983

Van Dover, C. L., Arnaud-Haond, S., Gianni, M., Helmreich, S., Huber, J. A., Jaeckel, A. L., et al. (2018). Scientific rationale and international obligations for protection of active hydrothermal vent ecosystems from deep-sea mining. *Mar. Policy* 90, 20–28. doi: 10.1016/j.marpol.2018.01.020

Van Dover, C. L., Aronson, J., Pendleton, L., Smith, S., Arnaud-Haond, S., Moreno-Mateos, D., et al. (2014). Ecological restoration in the deep sea: desiderata. *Mar. Policy* 44, 98–106. doi: 10.1016/j.marpol.2013.07.006

Vanreusel, A., Hilario, A., Ribeiro, P A., Menot, L., and Martínez Arbizu, P. (2016). Threatened by mining, polymetallic nodules are required to preserve abyssal epifauna. *Sci. Rep.* 6:26808. doi: 10.1038/srep26808

Vierros, M., Suttle, C., Harden-Davies, H., and Burton, G. (2016). Who owns the ocean? Policy issues surrounding marine genetic resources. *Limnol. Oceanogr.* 25, 29–35. doi: 10.1002/lob.10108

Wakefield, J. R., and Myers, K. (2016). Social cost benefit analysis for deep sea minerals mining. *Mar. Policy* 22:2016. doi: 10.1016/j.marpol.2016.06.018

Wedding, L. M., Reiter, S. M., Smith, C. R., Gjerde, K. M., Kittinger, J. M., Friedlander, A. M., et al. (2015). Managing mining of the deep seabed. *Science* 349, 144–145. doi: 10.1126/science.aac6647

Woodwell, G. M. (2011). Curb deep-sea mining now. *Nature* 471:36. doi: 10.1038/471036a

World Bank (2017). *Precautionary management of deep sea minerals. Pacific Possible Background Paper No. 2*. Washington, D.C: World Bank Group doi: 10.1596/28135

Worm, B., Barbier, E. B., Beaumont, N., Duffy, J. E., Folke, C., Halpern, B. S., et al. (2006). Impacts of biodiversity loss on ocean ecosystem services. *Science* 314, 787–790. doi: 10.1126/science.1132294

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.