JACOBS UNIVERSITY

Interdisciplinary Assessment of Deep-Sea Mining Impacts: From Impact to Policy and Implications for Sustainable Development

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
in Geosciences

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List of abbreviations

Chemical compounds:

Ag	Silver
Au	Gold
Al	Aluminum
Co	Cobalt
Cu	Copper
Dy	Dysprosium
Fe	Iron
Mn	Manganese
Mo	Molybdenum
Nb	Niobium
Nd	Neodymium
Ni	Nickel
O	Oxygen
S	Sulfur
Te	Tellurium
Th	Thorium
Ti	Titanium
W	Tungsten
Zn	Zinc
Zr	Zirconium
REE	Rare Earth Elements
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
N_2O	Nitrous oxide
NO_X	Nitrogen oxides
SO_X	Sulfur oxides
NMVOC	Non-methane volatile organic compounds
PM	Particulate matter
- eq.	- equivalent.
GHG	Greenhouse gases

Marine fuels:

HFO	Heavy Fuel Oil
LNG	Liquefied natural gas
MDO	Marine Diesel Oil
MGO	Marine Gas Oil

International institutions and agreements:

1994 IA	Agreement relating to the implementation of Part XI of UNCLOS
2030 Agenda	2030 Agenda for Sustainable Development
2006 IPCC Guidelines	2006 Guidelines for National Greenhouse Gas Inventories
BSSIPC	Bismarck-Solomon Seas Indigenous Peoples Council
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
ISA	International Seabed Authority
ITLOS	International Tribunal for The Law of the Sea
KP	Kyoto Protocol
LTC	Legal and Technical Commission (of the ISA)
MARPOL	International Convention for the Prevention of Pollution from Ships
MEA	Multilateral Environmental Agreement
MEPC	Marine Environmental Protection Committee (of MARPOL)
PA	Paris Agreement
UNCLOS	United Nations Convention on the Law of the Sea
UNFCCC	United Nations Framework Convention on Climate Change
SDC	Seabed Disputes Chamber (of ITLOS)
SDG	Sustainable Development Goal
SPC	Secretariat of the Pacific Community
UNDRIP	United Nations Declaration on the Rights of Indigenous Peoples

Terminology:

CAB	Coastal Area of Benefit
CCZ	Clarion-Clipperton Zone
CF	Conversion Factor
CHM	Common Heritage of Mankind
CBDR-RC	Common but Differentiated Responsibilities and Respective Capabilities
DWT	Deadweight
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Index
EF	Emission factor
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
ETS	Emissions Trading Scheme
IRZ	Impact Reference Zone
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
NDC	Nationally Determined Contribution
NGO	Non-Governmental Organization
PRZ	Preservation Reference Zone
REMP	Regional Environmental Management Plan
SEEMP	Ship Energy Efficiency Management Plan
SIA	Social Impact Assessment
SIMP	Social Impact Management Plan

Research projects:

DISCOL	DISturbance and re-COLonization experiment
DOMES.	Deep Ocean Mining Environmental Study
JET	Japan's Deep-Sea Impact Experiment
JPI-O	Joint Programming Initiative Healthy and Productive Oceans
MIDAS	Managing Impacts of Deep Sea Resource Exploitation

Definitions:

The Area
Pursuant to Article 1(1) of UNCLOS, 'Area' means "the seabed and ocean floor and subsoil thereof, beyond the limits of national jurisdiction."

Activities in the Area
Pursuant to Article 1(3) of UNCLOS, 'activities in the Area' means "all activities of exploration for, and exploitation of, the resources of the Area." As specified in the ITLOS Advisory Opinion, this includes extraction, in-situ (i.e., vertical) transportation and shipboard-processing of marine minerals and their transport directly above the mine site but not the ex-situ transport via ship from the mine site to a point on land (ITLOS 2011).

Pollution of the marine environment
Pursuant to Article 1(4) of UNCLOS, 'pollution of the marine environment' means "the introduction by man, directly or indirectly, of substances or energy into the marine environment, including estuaries, which results or is likely to result in such deleterious effects as harm to living resources and maritime life, hazards to human health, hindrance to marine activities, including fishing and other legitimate uses of the sea, impairment of quality for use of sea water and reduction of amenities."

Summary

Summary

Marine mineral resources (i.e., manganese nodules, ferromanganese crusts, and seafloor massive sulfide deposits) contain significant amounts of metals, which could, in the future, serve as raw materials to produce various goods. These include, but are not limited to, construction materials, electronic devices like computers and smartphones, renewable energy technology, and batteries. Several trends like population growth, industrialization, digitization, and the intended large-scale transition to a low-carbon economy have caused the global demand for metals to increase, evoking fears of future supply shortages. Furthermore, proponents of deep-sea mining increasingly praise the new industry, which remains in the exploration stage, as a means to foster sustainable development and mitigate climate change. Moreover, several studies have pointed out that deep-sea mining may be preferable to conventional terrestrial mining, as it would neither require the removal of vegetation and overburden nor the relocation of local communities. However, opponents have criticized this positive attitude towards deep-sea mining, raising concerns about its broad, significant, and long-lasting environmental and social impacts. The potential consequences of industrial-scale deep-sea mining have been studied over the past decades, although with different intensities. The direct biological and geochemical impacts resulting from the removal of marine mineral deposits at the seafloor and the dispersion of particle plumes in the water column have, for example, been the subject of several environmental impact assessments, whereas other impacts, such as the emission of greenhouse gases and air pollutants, and the social implications of deep-sea mining, have only received limited attention so far.

To address some of the persisting knowledge gaps and to contribute to the holistic and interdisciplinary assessment of deep-sea mining, this thesis, firstly, investigates the emerging industry's potential environmental, social, economic, and legal implications (see chapter 2). Secondly, it quantifies the greenhouse gas emissions and air pollutants released annually by a hypothetical manganese nodule mining operation in the Clarion-Clipperton Zone (see chapter 3) and explores how these can be regulated within the context of international environmental law and policy (see chapter 4). Lastly, this thesis discusses in how far deep-sea mining can contribute to the United Nation's 2030 Agenda on Sustainable Development and achieving the Sustainable Development Goals (see chapter 5).

Following the introduction (Chapter 1), Chapter 2 of this thesis demonstrates that deep-sea mining is a highly complex issue, which involves many stakeholders with often opposing views and opinions. Carrying out deep-sea mining operations requires intense interdisciplinary and integrated research to minimize environmental, economic, and social costs.

Chapter 3 provides the methodology to quantify greenhouse gas emissions and air pollution resulting from deep-sea mining operations, using a hypothetical manganese nodule mining operation in the Clarion-Clipperton Zone at 5,000 m depth with subsequent transportation of the recovered minerals to Mexico, Canada, and Cuba as a case study. The assessment, which is based on three different energy demand estimates of mineral extraction and shipboard processing provided in the literature and own calculations of the ex-situ transport component, shows that the annual greenhouse gas emissions of a 3 million tons (dry weight) nodule mining operation range between 82,600 - 482,000t CO_2-equivalent (-eq.), 1,880 - 11,197t SO_2-eq., and 1,390–8,734 t NO_x-eq., respectively. The exact magnitude of emissions depends on factors such as engine loads, their specific fuel oil consumption, and the speed of the transport vessels.

Chapter 4 demonstrates that greenhouse gas emissions resulting from deep-sea mining in areas beyond national jurisdiction are currently not adequately regulated. The chapter analyzes if and how these emissions could be incorporated in the international climate regime (United Nations Framework Convention (UNFCCC) and Paris Agreement (PA)), the international shipping regime (International Maritime Organization (IMO) and International Convention for the Prevention of Pollution from Ships (MARPOL)), and the international deep-sea mining regime (United Nations Convention on the Law of the Sea (UNCLOS)) and rules, regulations and procedures put forward by the International Seabed Authority (ISA)). Moreover, it explores which policy instruments (i.e., informational measures, command-and-control instruments, and market-based mechanisms) could be applied within the respective regimes to achieve stabilization or mitigation of these emissions. The chapter recommends that greenhouse gas emissions resulting from the excavation, vertical transport, and shipboard processing regime are regulated under the deep-sea mining regime. The ISA, as a sectoral organization with no pre-established approach to climate change mitigation, has more flexibility with respect to selecting sector-specific climate change mitigation measures. Moreover, as an international environmental administration, it has a wider regulatory reach as it can target both public and private actors with its regulations. Lastly, the ISA has previously considered the issue and thus demonstrates a certain awareness and potential interest in regulating the issue. In any case, the ISA appears to be the proper forum to initiate a dialogue with the IMO and UNFCCC on the matter.

Chapter 5 considers the environmental, economic, social, and legal implications of deep-sea mining from a sustainability perspective. Specifically, it explores if and how deep-sea mining can contribute to sustainable development, the need for which has recently been consolidated by the United Nations in their 2030 Agenda for Sustainable Development and the associated Sustainable Development Goals (SDGs). The assessment shows that deep-sea mining is mainly incompatible with SDG 12 ('sustainable production and consumption') and SDG 14 ('sustainable life under water'). It may, however, be compatible with SDG 1 ('ending poverty'), SDG 2 ('ending hunger'), SDG 3 ('health, well-being'), SDG 10 ('sustainable and modern energy'), and SDG 13 ('combat climate change and its impacts'), provided that negative impacts are reduced as far as possible through the implementation and enforcement of strict regulations, environmental, financial, and social impact management plans, the application of the precautionary approach, and good governance.

Lastly, Chapter 6 concludes the dissertation with a summary of the dissertation, an outlook, and recommendations for science and policymaking.

Introduction

Chapter 1: Introduction

Deep-sea mining describes the recovery of marine mineral resources, specifically of manganese (Mn) nodules, ferromanganese (FeMn) crusts, and seafloor massive sulfide (SMS) deposits, from the deep seabed, which are subsequently transported to shore and metallurgically processed on land to extract various metals (Mero 1965; Francheteau et al. 1979; Halbach et al. 1982; Petersen et al. 2016). Deep-sea mining operations can occur both within and beyond national jurisdiction, governed by the respective coastal country and by the International Seabed Authority (ISA), respectively. The ISA has been established by the United Nations Convention on the Law of the Sea (UNCLOS) to administer marine mineral resources on behalf of all humankind. Deep-sea mining consists of three types of activities: 1) the extraction, vertical transport, and shipboard processing of marine minerals recovered from the seafloor, 2) their transport to shore using bulk carrier vessels, and 3) their metallurgical treatment in processing facilities on land (SPC 2013a; SPC 2013b; SPC 2013c).

Presently, deep-sea mining is considered technologically challenging and economically unfeasible. However, the development of suitable mining equipment has advanced considerably in recent years, particularly concerning the mining of Mn nodules and SMS deposits and may soon make commercial deep-sea mining possible. Furthermore, the Mining Code, which will eventually regulate the exploration and exploitation of marine mineral resources in the international seabed, is now at an advanced draft stage and may shortly provide a clear legal framework for commercial deep-sea mining (ISA 2021). Moreover, several global trends like rapid population growth, the increasing industrialization and digitalization, and the growing desire to transition to renewable energy and electromobility have caused the demand for metals to increase and re-ignited the interest of various stakeholder groups in deep-sea mining (Koschinsky et al. 2018; Sparenberg 2019). Hence, as deep-sea mining is closer to becoming a reality, it is urgently necessary for society to carefully assess the costs and benefits of the new emerging industry to make a well-founded decision in favor of or against engaging in it.

Marine mineral resources were first scientifically described during an expedition of the British HMS Challenger, which circumnavigated the world between 1872 and 1876 to "produce the most comprehensive knowledge of the oceans through temperature and depth measurements, chemical and physical analysis of seawater, specimen collection and natural history observations" (Zuroski 2017: 107; Sparenberg 2019). During their almost 70,000 nautical mile (NM) long journey, the expedition participants recovered large amounts of small, dark grey, potato-shaped mineral concretions from the seafloor of the Indian, the Atlantic, and the Pacific Ocean. The scientists onboard the vessel soon realized that these nodules were rich in metals, particularly manganese peroxide[1], which was a valuable resource at the time (Glasby 2002; Glasby et al. 2015). Despite this, they did not believe that Mn nodules would ever become a commercially exploitable resource (Murray and Renard 1891; Glasby 2002; Sharma 2010; Sparenberg 2019). Therefore, the nodules were treated as mere 'mineral curiosities and displayed as such in museums and rock collections for the decades to come (Sparenberg 2019: 843).

The interest in commercially mining Mn nodules only emerged in the second half of the 20th century, when the American mining engineer, John L. Mero, described Mn nodules as a nearly limitless and virtually inexhaustible source of metals in his book 'The Mineral Resources of the Sea' (1965). Moreover, he claimed that Mn nodules could relatively easily be recovered and that the deep-sea mining industry would mature within the next 20 years (Mero 1965; Glasby 2002; Sparenberg 2019). Mero's positive outlook coupled with the perceived risk of severe supply shortages triggered, for example, by the 1969 Nickel Crisis (supply shortages in Europe due to labor strikes in Canadian mines), the Club of Rome's predictions of severe supply shortages, and increases in metal commodity prices published in the report "Limits to Growth" (1972), and the ongoing resource conflict between the industrialized North and the developing South sparked the interest of several nations to develop an alternative and independently accessible source of metals in the deep-sea (Meadows et al. 1972; Sparenberg 2019). Subsequently, mining and engineering companies, mainly from industrialized countries, formed several multi-national consortia to study the formation, occurrence, and resource potential of different types of marine mineral deposits (Glasby 2002; Sparenberg 2019). Furthermore, they engaged in developing suitable technological solutions to harvest the mineral deposits at the seafloor, lift them to the surface and process them metallurgically on land. Their efforts culminated in a number of pilot mining projects in the ocean and pilot plant operations on land (Glasby 2002; Das and Anand 2017). Retrospectively, the period from 1972 to 1982 is often called the "golden era for manganese nodule research" (Glasby 2002: 162). However, the initial excitement was replaced by resignation in the early 1980s, when metal commodity prices decreased due to increased exploration of terrestrial mineral ores and the relaxing North-South relationship, and insurmountable technological obstacles mainly related to the difficulty of operating equipment at 4,500 m depth rendered deep-sea mining both economically and technologically unfeasible (Sparenberg 2019). Consequently, the commercial interest of the industrialized countries in deep-sea mining mainly ceased.

[1] The term "peroxide" originates from a report written by J. J. Buchanan, expedition chemist onboard the HMS Challenger in the 18th century. The quote is taken from Glasby et al. (2015: 72).

The second high-interest phase in deep-sea mining research and development emerged during the 1990s, mainly led by state-owned companies and government institutes from China, Japan, South Korea, and India. Their engagement was mainly driven by geostrategic concerns, specifically a perceived vulnerability to supply shortages in the respective countries and the economic prospects of deep-sea mining. Contrary to this, the industrialized countries' interest in deep-sea mining mainly shifted to environmental impact research (Glasby 2002; Sparenberg 2019).

The global interest in deep-sea mining resurfaced at the turn of the millennium when China briefly interrupted or decreased the export of rare earth elements (REE), on which the country holds a virtual monopoly (Looney 2011; Humphries 2013; Klare 2013; Smith Stegen 2015). As the global demand for REEs, which are essential raw materials for the production of high-tech and green technology goods, was and continues to be expected to increase substantially over the following decades, the international export limitations evoked fears of supply shortages similar to those of the early 1970s. This development made several countries reconsider their attitude towards deep-sea mining, despite ongoing profitability concerns (Normile 2010; Sparenberg 2019).

Nowadays, deep-sea mining is increasingly discussed in the context of climate change mitigation and sustainable development, as it could provide the vast amounts of metals needed to shift to renewable energy and electromobility and offer several countries the possibility to generate additional income and diversify their economy (Christiansen et al. 2019; Levin et al. 2020; Paulikas et al. 2020). The United Nations have recently highlighted the need for sustainable development in the 2030 Agenda for Sustainable Development (2030 Agenda), which is a "plan of action for people, planet and prosperity" and "seeks to strengthen universal peace in larger freedom" (A/RES/70/1: Preamble). The 2030 Agenda is associated with 17 Sustainable Development Goals (SDGs), including, for example, "end[ing] poverty in all its forms everywhere" (SDG 1), "end[ing] hunger" (SDG 2), "ensur[ing] healthy lives and promot[ing] well-being for all" (SDG 3), "ensur[ing] access to affordable, reliable, sustainable and modern energy for all" (SDG 7), "promot[ing] sustained, inclusive, and sustainable economic growth, full and productive employment and decent work for all" (SDG 8), "ensur[ing] sustainable consumption and production patterns" (SDG 12), "tak[ing] urgent action to combat climate change and its impacts" (SDG 13), and "conserve[ing] and sustainably us[ing] the oceans, seas and marine resources for sustainable development" (SDG 14) (A/RES/70/1: 14).

Several studies point out that deep-sea mining may not only provide access to an additional or alternative source of metals but may even be preferable to conventional terrestrial mining from an environmental and social perspective. They mention that deep-sea mining would neither require removing vegetation and overburden nor relocating local communities (Hein and Koschinsky 2014; Batker and Schmidt 2015; Koschinsky et al. 2018). Furthermore, deep-sea mining, at least the activities carried out at sea, would rely on mobile infrastructure that could be removed and reused after the closing of a mine. Moreover, proponents of deep-sea mining often point out the declining metal content of terrestrial ores, which will likely force mining operations to expand more rapidly and into increasingly remote territories, intensifying environmental and social conflicts (Calvo et al. 2016; Mudd 2020).

However, an increasing number of studies raise concerns about the substantial and potentially long-lasting environmental and social impacts of deep-sea mining (Koschinsky et al. 2018; Billet et al. 2019; Christiansen et al. 2019). For instance, removing marine mineral deposits at the seafloor will cause large-scale destruction of deep-sea habitats (Giere 1993; Vanreusel et al. 2016; Gollner et al. 2017; Weaver and Billet 2019). Furthermore, the operation of cutter and collector vehicles on the seabed, as well as the discharge of the sediment and water mixture resulting from the lifting and rinsing of the marine minerals onboard the mining vessel at the sea surface may create fine-grained particle plumes, which may extend far beyond the mine sites (SPC 2013b; SPC 2013a; SPC 2013c; Gillard et al. 2019; Weaver and Billet 2019). When settling, these particles may blanket marine organisms and clog the feeding apparatus of filter-feeding organisms. Deep-sea mining may also cause geochemical changes at the seafloor and in the water column, which may negatively affect local benthic and pelagic ecosystems (Fritsche et al. 2001; Hauton et al. 2017; Koschinsky et al. 2018; Paul et al. 2018). Additional adverse effects of deep-sea mining may include noise and light pollution and the release of greenhouse gas emissions and air pollutants from the mining vessel due to fossil fuel combustion (Heinrich et al. 2020). Overall, the environmental impacts occurring at the seafloor and in the water column may negatively affect essential ecosystem functions and services such as food supply on different trophic levels and carbon sequestration (Niner et al. 2018).

Adverse social impacts of deep-sea mining may, for example, occur where deep-sea mining negatively affects other economic sectors, such as fishery and tourism (Roche and Bice 2013; Folkersen et al. 2018a; Koschinsky et al. 2018). Furthermore, culturally or spiritually important sites in the ocean, which play a significant role in non-western cultures, could be disturbed or destroyed (Roche and Bice 2013; Filer and Gabriel 2018; Childs 2020). Moreover, deep-sea mining can indirectly affect terrestrial mining communities if the additional supply of certain metals significantly alters commodity prices and reduces the demand for metals from terrestrial mines (Dacey 2020).

The potential impacts of deep-sea mining have been thoroughly studied over the past years, albeit with different intensities. The direct biological and geochemical impacts resulting from the removal of marine mineral deposits at the seafloor and the dispersion of the particle plumes in the water column have, for example, been the subject of the German Disturbance and Re-Colonization Experiment (DISCOL, 1989) and subsequent return visits, the Japan Deep-Sea Impact Experiment (JET, 1994-1997), the Managing Impacts of Deep-Sea Resource Exploitation project (MIDAS, 2013-2015), and most recently the Joint Programming Initiative Oceans' MiningImpact project (2015-2017 and 2018-2022) (Foell et al. 1990; Fukushima 1995; MIDAS 2013; JPI Oceans 2014). Other impacts, such as noise and light pollution, the emission of greenhouse gases and air pollutants, and the social impacts of deep-sea mining, have only received limited attention so far (Weaver and Billet 2019; Heinrich et al. 2020).

A holistic assessment of deep-sea mining impacts, which considers not only the environmental but also the social, economic, and legal implications of deep-sea mining, is, however, necessary to determine if the benefits that could potentially be obtained from deep-sea mining could outweigh its costs. In this regard, a comprehensive and thorough assessment can help answer whether deep-sea mining can contribute to achieving the SDGs. In an attempt to address some of the persisting knowledge gaps, specifically regarding the quantification and regulation of greenhouse gas emissions and air pollution arising from deep-sea mining operations, and to contribute to the holistic and interdisciplinary assessment of deep-sea mining, taking into particular account the SDGs, this dissertation seeks to answer the following four research questions:

1) What are the environmental, social, economic, and legal implications of deep-sea mining (current state of research)?
2) How can the greenhouse gas emissions and air pollution caused by deep-sea mining operations be quantified, and what impact would these emissions have in terms of global warming, acidification, and photochemical ozone formation?
3) How could greenhouse gas emissions caused by deep-sea mining in areas beyond national jurisdiction be regulated on an international level?
4) To what extent can deep-sea mining contribute to sustainable development, specifically to reaching the SDGs?

From here on, this dissertation will be structured as follows:

Chapter 1 - Introduction - introduces the topic of deep-sea mining and outlines the research questions this dissertation aims to answer.

Chapter 2 - Implications of deep-sea mining - describes the current state of research and serves as background information for the following chapters. This article describes the formation, occurrence, and resource potential of the three different types of marine mineral deposits and provides an overview of environmental, social, legal, and economic implications of deep-sea mining in areas within and beyond national jurisdiction.

Chapter 3 – Quantification of emissions to air - zooms in on one of the impacts that has not received any attention so far in assessing deep-sea mining impacts. The article provides a methodology for quantifying emissions caused by a hypothetical nodule mining operation in the Clarion-Clipperton Zone and outlines to what extent these emissions may affect global warming, acidification, and the formation of photochemical ozone. Moreover, the chapter touches on how these emissions could be addressed from a policy perspective.

Chapter 4 - Regulation of greenhouse gas emissions from deep-sea mining - picks up on the question of how greenhouse gas emissions released by deep-sea mining could be regulated on an international level, considering particularly the climate change regime, the international shipping regime, and the deep-sea mining regime.

Chapter 5 - Contribution of deep-sea mining to sustainable development - zooms back out and considers deep-sea mining from an interdisciplinary perspective. This article investigates to what extent deep-sea mining within and beyond the limits of national jurisdiction can contribute to sustainable development.

Chapter 6 - Conclusion, recommendations, and outlook - summarizes the findings of the dissertation, provides recommendations and outlines what kind of further work is needed to thoroughly assess whether the benefits deep-sea mining may offer are worth the costs.

Chapter 7 - Other scientific work – provides an overview over publication and other scientific work that was completed in parallel to working on this dissertation.

Chapter 2: Interdisciplinary research on deep-sea mining

Title of publication:

Deep-sea mining: Interdisciplinary research on potential environmental, legal, economic, and societal implications

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Published in:

Integrated Environmental Impact Assessment and Management (2018): 14 (6): 672-691,
DOI: https://doi.org/10.1002/ieam.4071.

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Abstract

Deep-sea mining refers to the retrieval of marine mineral resources such as manganese nodules, ferromanganese crusts, and seafloor massive sulfide deposits, which contain a variety of metals that serve as crucial raw materials for a range of applications, from electronic devices to renewable energy technologies to construction materials. With the intent of decreasing dependence on imports, supporting the economy, and potentially even overcoming the environmental problems related to conventional terrestrial mining, a number of public and private institutions have rediscovered their interest in exploring the prospects of deep-sea mining, which had been deemed economically and technically unfeasible in the early 1980s. To date, many national and international research projects are grappling to understand the economic, environmental, social, and legal implications of potential commercial deep-sea mining operations: a challenging endeavor due to the complexity of direct impacts and spillover effects. In this paper, we present a comprehensive overview of the current state of knowledge in the aforementioned fields as well as a comparison of the impacts associated with conventional terrestrial mining. Furthermore, we identify knowledge gaps that should be urgently addressed to ensure that the world at large benefits from safe, efficient, and environmentally sound mining procedures. We conclude by highlighting the need for interdisciplinary research and international cooperation.

1 Introduction

Deep-sea mining refers here to the excavation of three types of marine mineral deposits on the seafloor: polymetallic or manganese (Mn) nodules (Mero 1965), ferromanganese (FeMn) crusts (Halbach et al., 1982), and seafloor massive sulfide (SMS) deposits (Francheteau et al. 1979; Petersen et al. 2016). These different types of deposits differ with respect to their physical and chemical properties, formation, metal content, geographic distribution, and extraction technologies as well as the environmental and social impacts associated with mining them. All deposits contain valuable metals. Whereas Mn nodules and FeMn crusts are of interest because of their high Cu, Co, and Ni content, SMS deposits are likely to be mined to extract Cu, Zn, Au, and Ag (Hoagland et al. 2010). Some deposits also host substantial quantities of rare earth elements (REE) and other high-tech elements, which are important raw materials for the manufacture of renewable energy and information technology but are currently not considered target metals. To date, these metals are obtained from terrestrial mines and, to a much smaller degree, from recycled material. Meeting the metal demand of a rapidly increasing world population and the economic growth of transitioning countries such as India and China will require either the expansion of existing mining projects or the establishment of new ones. This development will, however, intensify the already pronounced environmental and social impacts associated with terrestrial mining, such as habitat degradation, air and water pollution, toxic wastes, and the dislocation of local inhabitants. Deep-sea mining, which will take place offshore mostly far away from any coastline would be associated with adverse impacts that will be different from terrestrial mining impacts and need to be considered in the respective context of the environmental setting of the deposits (Ramirez-Llodra et al. 2011).

To overcome these environmental challenges, to improve economic performance and to secure an independent metal supply, public and private institutions have once more started exploring the prospects of commercial deep-sea mining, which for more than 20 years had been deemed economically unfeasible. In parallel to financial modeling and environmental research by various public and private institutions, the International Seabed Authority (ISA) has started to develop rules and regulations for the exploration and exploitation of deep-sea mineral deposits. This development is unique given that environmental regulation is typically retrofitted long after the commercialization of the activity, as for example, in the case of terrestrial mining. Ensuring the development of effective and efficient regulation requires a multidisciplinary assessment of deep-sea mining, including environmental impact assessment, financial assessment, socioeconomic impact assessment, and compliance with the legal framework. Further research on this complex topic therefore needs interdisciplinary collaboration among natural and social scientists, economists, engineers, and legal scholars. Against this background, we present a wide-reaching overview of the current state of knowledge in relevant spheres (economy, environment, society, and law), and we identify knowledge gaps that need to be addressed ensure that current and future generations can benefit from maximally safe, economically efficient, and environmentally sound access to marine mineral resources.

Following this introduction, we briefly describe the three different types of deep-sea mineral deposits and potential environmental impacts associated with deep-sea mining activities. Next, we present a comparison to terrestrial mining and elaborate on legal considerations regarding the development of regulatory frameworks. Together, these aspects form the analytical and institutional frame for the subsequent analysis of societal perception and interpretations of deep-sea mining by taking into account the economic considerations of public and private investors and highlighting social and psychological concerns. Reasoning from this interconnectedness of perspectives, we call for an increase in interdisciplinary research efforts. In the present article, we focus solely on the extraction of marine minerals from the deep sea and the impacts thereof. We do not consider any impacts associated with refining and processing of marine mineral deposits, because they are expected to be analogous to those arising from the processing of terrestrial minerals (as in the case of SMS deposits) or are still highly uncertain (as in the case of Mn nodules and FeMn crusts). That topic deserves discussion of its own.

2 Types of marine mineral deposits

2.1 Polymetallic or manganese nodules

Mn nodules are very slow-growing (mm-cm*Ma-1), potato-shaped mineral concretions, which form through the precipitation of metals from sediment porewater (diagenetic formation) and seawater (hydrogenetic formation), or a combination thereof (Figure 1). Mn nodules mainly consist of intergrown concentric layers of Mn and Fe oxides and contain substantial quantities of Cu, Co, Ni, Mo, Pt, Te, and Zn, as well as REEs (Hein and Koschinsky 2014). Mn nodules occur on sediment-covered abyssal plains in water depths of 3,000 to 6,000 m and are particularly abundant in the Clarion-Clipperton Fracture Zone (CCZ), the Peru Basin, the Penrhyn-Samoa Basin, and the Central Indian Ocean Basin (Hein et al. 2013). In legal terms, Mn nodules are mainly located in ‘the Area,’ which is one of the maritime zones defined in the United Nations Convention on the Law of the Sea (UNCLOS) and is described as “the seabed and ocean floor and subsoil thereof, beyond the limits of national jurisdiction” (UNCLOS, Article 1(1)). The ISA, a global organization that regulates and administers the exploitation of resources in the Area, is responsible for governing deep-sea mining. In the early 2000s, the ISA entered into 15-year contracts with several European, Asian, and Pacific countries, granting them exclusive rights to explore sectors of the seabed for the prospects of deep-sea mining (Lodge 2015) (Figures 2 and 3). Recent calculations by Petersen et al. (2016) predict the resource potential of Mn nodules in the CCZ to clearly surpass that of equivalent terrestrial mineral deposits. For instance, the CCZ alone is expected to contain 21 billion t of Mn nodules (dry weight) potentially containing some 6,000 million t of Mn, 270 million t of Ni, and 44 million t of Co (Hein et al. 2013; Hein et al. 2015; Petersen et al. 2016). Deposited on the surface layer of the sediment, Mn nodules could be extracted using a collector vehicle coupled with a vertical transport system that lifts them to a support vessel at the sea surface. Current basic design concepts focus on the use of hydraulic, mechanical, or hybrid collector systems, or alternatively bucket- or dredge-type collectors for gathering nodules, along with a vertical transport mechanism such as a pipe, rope, or cable for lifting them to the surface (SPC 2013a).

Figure 1: *Manganese nodules on the sediment surface of the abyssal plain in the Clarion-Clipperton Zone, central NE Pacific (source: BGR) (Reprinted from Koschinsky et al. 2018).*

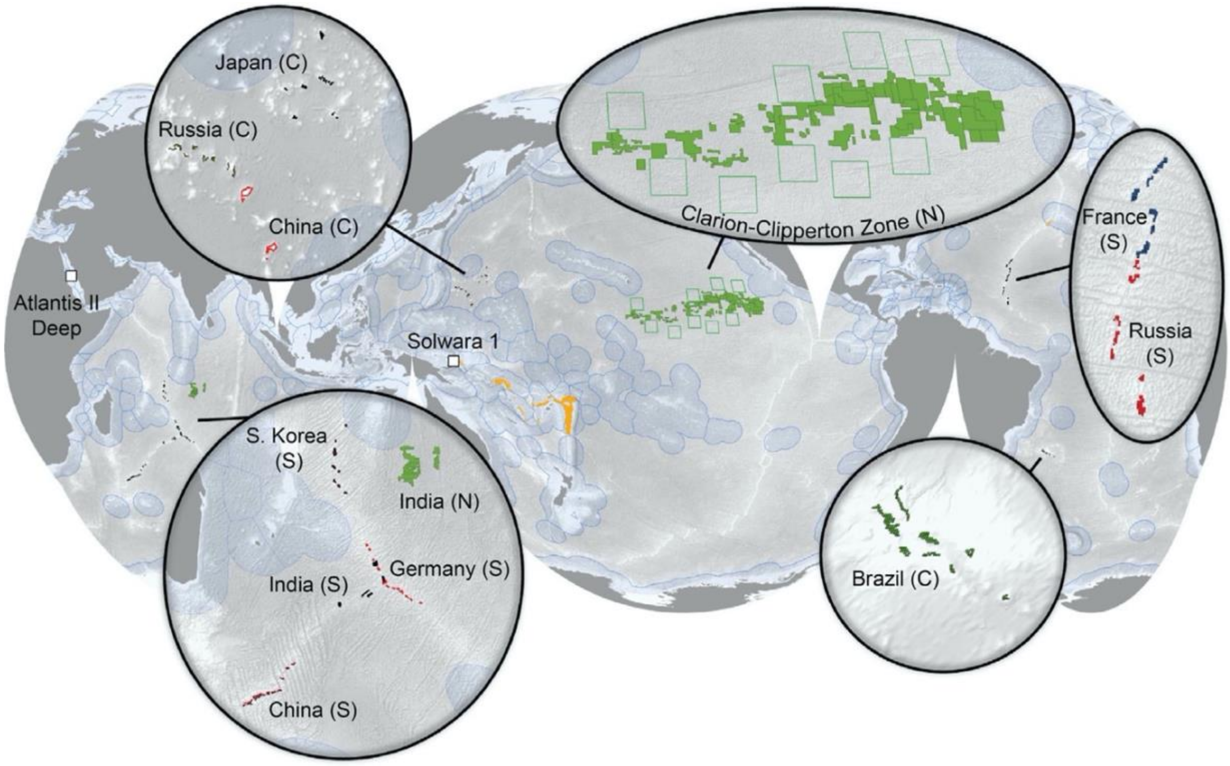

Figure 2: Locations of global exploration licenses for Mn nodules (N), Co-rich FeMn crusts (C) and seafloor massive sulfides (S for licenses within "the Area," orange for licenses within EEZs). Reprinted from Petersen et al. (2016) (Reprinted from Koschinsky et al. 2018).

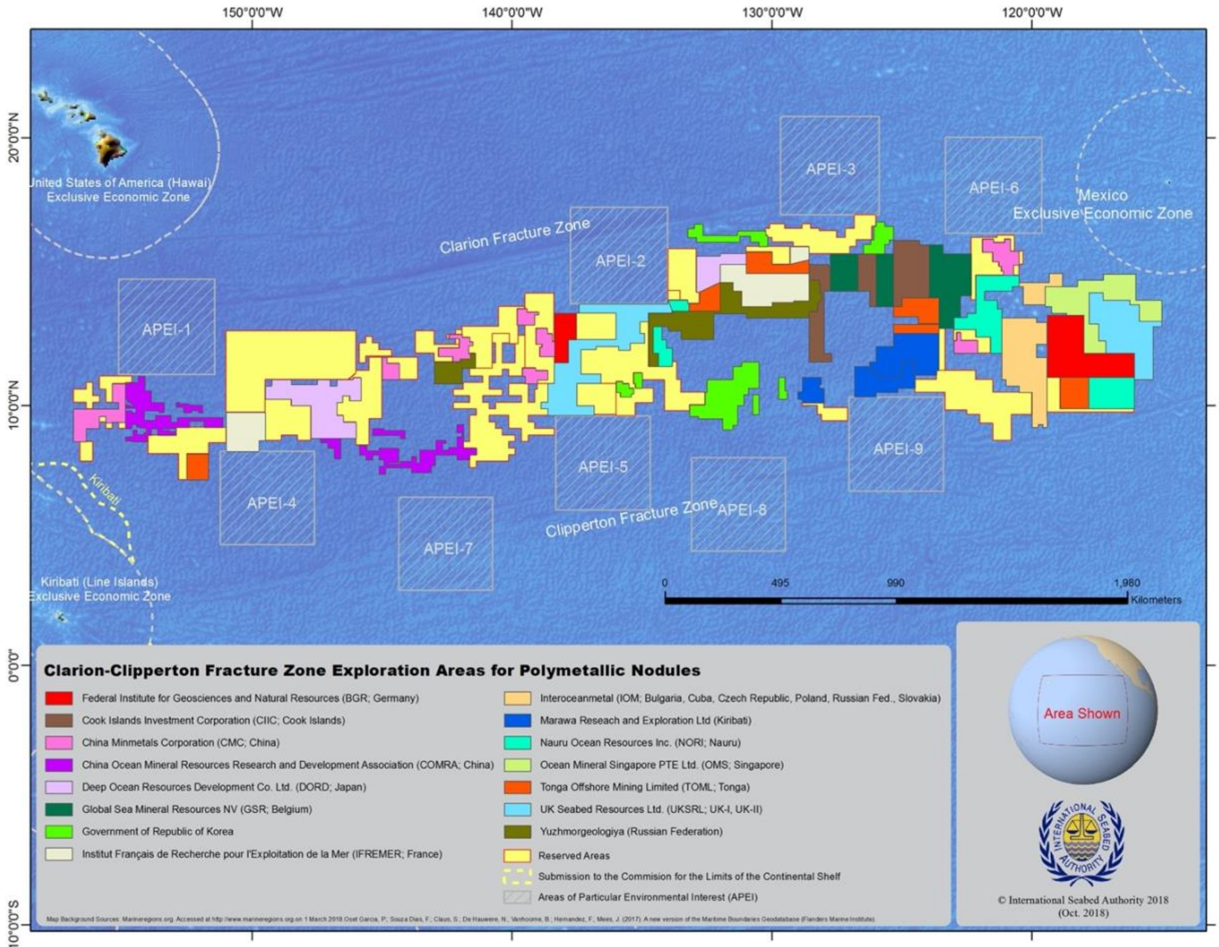

Figure 3: *Clarion-Clipperton Zone exploration areas for Mn nodules. The location of the 'Areas of Particular Environmental Interest' (APEI, 400 km by 400 km each) in the CCZ are shown as rectangles with a white outline. (Reprinted from https://www.isa.org.jm/maps and Koschinsky et al. 2018).*

2.2 Ferromanganese crusts

FeMn crusts are extremely slow-growing (mm*Ma-1) layers with known thickness of 1 to 26 cm, consisting of Mn and Fe oxides as well as significant quantities of Cu, Co, Ni, Mo, Te, REE, W, Ti, Th, Zr, Nb, and trace amounts of many other metals, including Pt bound in the oxide mineral structures (Halbach et al. 1982; Hein et al. 1992) (Figure 4). FeMn crusts form through the precipitation of metals from cold ambient seawater on the sediment-free slopes of seamounts. Crusts of best metal quality are primarily located in water depths from 800 to 2,500 m mostly in areas beyond national jurisdiction (Hein and Koschinsky 2014) (Figure 2). For instance, the Prime Crust Zone (PCZ), i.e., the area expected to become relevant for commercial FeMn crust mining, is located in the western Pacific Ocean and extends from the Hawaiian Islands in the east to the border of the Mariana Trench in the west. FeMn crusts can, however, also form in shallower water depths in areas within national jurisdiction, for example, in the Hawaiian island chain. This means they occur not only in the Area but also in territorial or archipelagic waters, exclusive economic zones (EEZs), or extended continental shelf areas over which the adjacent coastal states have either absolute sovereignty (territorial and archipelagic waters) or exclusive rights over living and non-living resources (EEZ and continental shelf) (UNCLOS). FeMn crusts are considerably more difficult to mine than Mn nodules, given that they are firmly attached to the rock substrate of slopes of seamounts (SPC 2013b). No feasibility concept for mining FeMn crusts has been made public to date.

Figure 4: *Ferromanganese crust piece (encrustation thickness up to 10 cm) strongly intergrown with phosphatized reef limestone, recovered at the Tropic Seamount (NE Atlantic) (Reprinted from Koschinsky et al. 2018).*

2.3 Seafloor massive sulfide deposits

SMS deposits (Figure 5) consist of metal-S compounds that form massive structures on and below the seafloor at water depths of about 250 to 4,000 m. They occur in geologically active areas along plate boundaries characterized by an abundance of hydrothermal vent systems or in shallower depths alongside volcanic chains as well as island arcs (Francheteau et al. 1979) (Figure 2). Thus, SMS deposits can be found both within the Area (particularly along midocean ridges) and within the EEZ of islands or coastal states. SMS deposits form through the precipitation of metals as a result of the interaction of cold, ambient seawater with very hot hydrothermal fluids that are very rich in metals and S (Hannington et al. 2005). Thus, SMS deposits contain substantial quantities of the metals Fe, Cu, Zn, Ag, and Au, as well as small amounts of REE (Monecke et al. 2014). In contrast to Mn nodules and FeMn crusts, SMS deposits grow much faster and form three-dimensional structures that extend irregularly into the seabed. Although this makes it difficult to reliably assess their resource potential and makes them considerably more complicated to extract, SMS deposits may be the first type of deep-sea deposits to be exploited commercially. Utilizing seafloor production tools and riser and lifting systems inspired by offshore oil and gas technology as well as land-based mining, the Canadian underwater mining company Nautilus Minerals has developed plans to begin commercial operations in the EEZ of Papua New Guinea in the near future (Filer and Gabriel 2018). However, recent success in a pilot test of continuous ore lifting technology by the Japanese Ministry of Economy, Trade and Industry (METI) and the Japan Oil, Gas and Metals National Corporation (JOGMEC) may indicate that Japan can take over the leading role in this field (METI 2017).

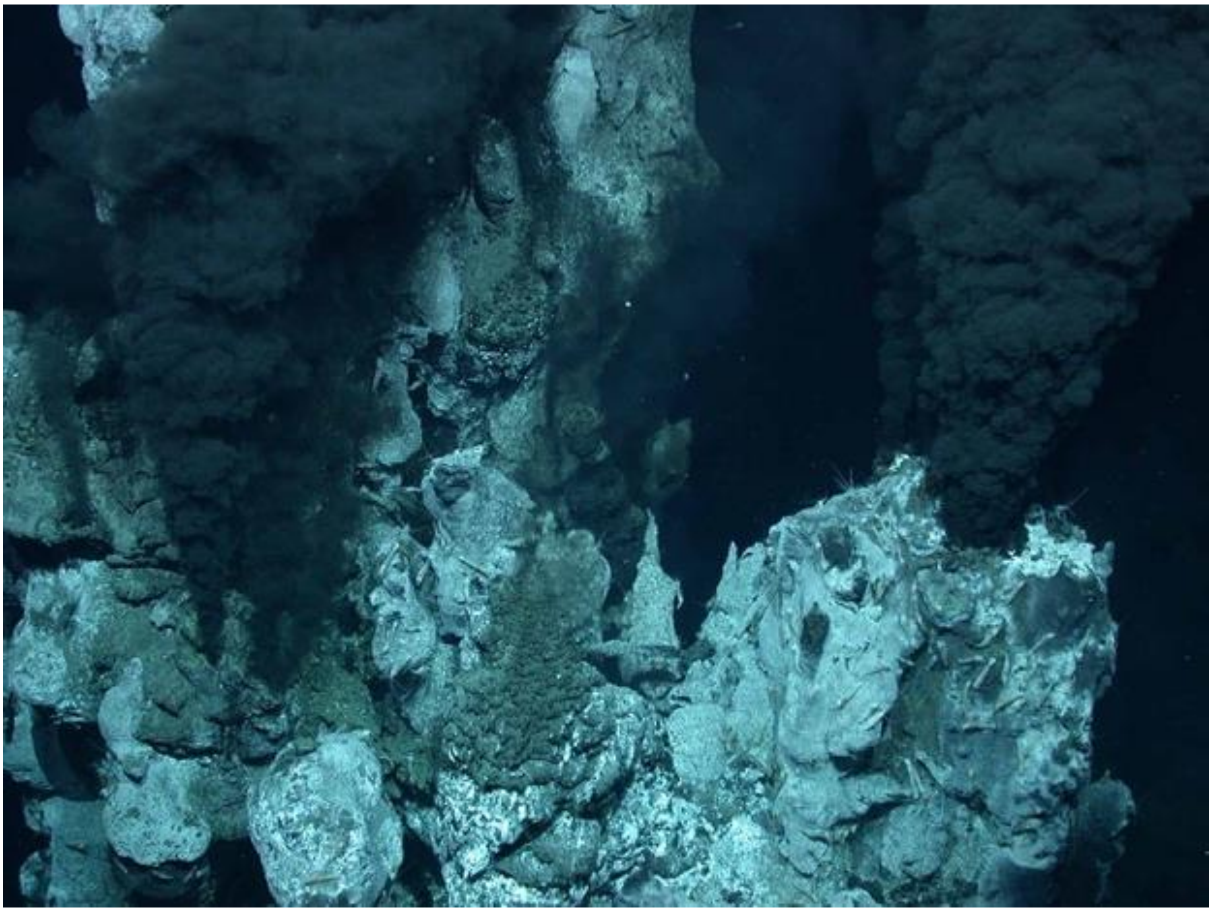

Figure 5: *Black smoker consisting of Fe–Cu–Zn sulfide minerals on the Mid- Atlantic Ridge (5°S); (Source: MARUM - Center for Marine Environmental Sciences, University of Bremen) (Reprinted from Koschinsky et al. 2018).*

3 Potential environmental impacts of deep-sea mining

Environmental impacts can occur along the entire deep-sea mining value chain (Figure 6). Because any impact happening on the sea surface, that is, any impact from the mining vessel or during transportation of the ore to land, and metallurgical processing of the minerals on land, will be comparable to other shipping-related or ore processing-related environmental impacts, we will not consider these in the present article. We will present all aspects that are specific for deep-sea mining, with a focus on mining of Mn nodules for which most information is available from experimental studies. In the following sections, we differentiate between direct biological impacts and geochemical impacts on the seafloor due to the collection of the ore (Figure 6, impact 1) and on impacts in the water column related to the lifting of the ore, the suspended bottom sediment plume, and the discharge of water and sediment from the mining ship back into deeper water layers (Figure 6, impact 3).

3.1 Biological impacts

3.1.1 Manganese nodules

The Mn nodule-rich sediment-covered abyssal plains, which host major abundances of Mn nodules, are inhabited by sessile and mobile megafauna (>2 cm), macrofauna (1-2 cm), meiofauna (<1 cm), and bacteria. These organisms do not directly photosynthesize but depend on nutrients produced by primary productivity in surface waters that sink to the seafloor primarily as fecal pellets (SPC 2013a; Vanreusel et al. 2016). In these areas characterized by soft sediment, many organisms live on top of or in the sediment (mostly within the upper 10 cm), whereas other species are directly attached to the Mn nodules (Giere 1993). Removing and compacting the upper sediment layer with deep-sea mining equipment will destroy organisms and considerably complicate the recolonization of the area. Furthermore, collector vehicles can stir up the sediment, dislocate animals, or create clouds of suspended sediment that would eventually cover areas larger than the mined area and bury bottom-dwelling organisms (Weaver et al. 2018). Depending on the particle concentration and lifetime of the plume, the resuspended sediment can kill or negatively affect the filter-feeders, which depend on a clean, sediment-free flow of water containing particles and animals for their food supply. It could also change microbial processes due to the changed geochemical conditions, which would impact further levels of the associated food chain.

Since the 1970s, the USA, Germany, France, and the Inter Ocean Metal Joint Organization (IOM, current members: Bulgaria, Cuba, Czech Republic, Poland, Russian Federation, and Slovakia), among others, have carried out numerous research cruises to anticipate the environmental impacts of commercial deep-sea mining operations (Yamazaki and Sharma 2001). The Deep Ocean Mining Environment Study (DOMES, 1972-1981), for instance, monitored the environmental impacts caused during two pilot mining tests conducted by Ocean Mining Inc. and Ocean Mining Associates (OMA) in the Pacific Ocean (Ozturgut et al. 1980). Another study, the German Disturbance and Re-Colonisation Experiment (DISCOL, 1989), simulated commercial nodule mining in the Peru Basin by systematically plowing an area of 11 km^2 (Foell et al. 1990). Mn nodules serve as solid substrate for many species. Removing the Mn nodules will thus cause severe permanent habitat destruction, which is detrimental for these sessile species. Several return visits to the disturbed sites were carried out over the past decades to study whether the infauna and ecosystem functioning can recover from a destruction by mining vehicles. Follow up research on the early DISCOL project (Thiel et al. 2001) showed that community composition and the overall level of biomass in the disturbed area in the Peru Basin (southeast Pacific) remained limited and altered, even 26 years later (Vanreusel et al. 2016). Recovery is highly variable in distinct ecosystems and among benthic taxa, and community changes may persist over geological time scales at directly mined sites (Gollner et al. 2017; Jones et al. 2017). The Japan Deep-Sea Impact Experiment (JET) studied the impact of re-sedimentation on the deep-sea sediment fauna and found a significant alteration of the sediment community (Kaneko et al. 1997). Furthermore, noise, vibration, and light associated with large-scale mining operations may affect the organisms' senses and cause discomfort, provoke avoidance reactions, or interfere with their ability to communicate and detect pray (Popper et al. 2003).

The ISA is currently discussing the establishment of Impact Reference Zones (IRZs), which are "representative of the environmental characteristics of a particular region to be used for assessing the effect of activities in the region on the marine environment," as well as Preservation Reference Zones (PRZs), which according to the ISA glossary describe "areas representative of the mine site in which no mining shall occur to ensure representative and stable biota of the seabed in order to assess any changes in the flora and fauna of the marine environment caused by mining activities" (ISA 2017).

Overall, the severity of the impacts will be site specific and will depend on the technology used in the mining operation. In any case, the actually mined area will be considerably smaller than the potentially mineable area because of the rough surface structure of the seabed and the low nodule coverage in many places (Sharma 2017). Further research needs to investigate whether a restoration of the disturbed area, for example, by providing alternative structures such as rock fragments as a solid substrate for the affected organisms, is possible and useful.

3.1.2 Ferromanganese crusts

FeMn crusts, which generally occur on the sediment-free slopes of seamounts, are largely inhabited by sessile epifauna such as corals, anemones, and sponges that may also extend above the seafloor (Fukushima 2007; Clark et al. 2010). The distribution of species varies depending on factors such as type of substrate, water depth, and current flow (Fukushima 2007; Clark et al. 2010). Due to the rocky substrate, swift currents, and lack of muddy sediment, FeMn crusts usually provide habitat for sessile species such as sponges and corals as well as filter feeders, rather than for burrowing fauna. Deep-sea mining operations will have a negative effect on species inhabiting the crust environment through the removal of rock substrate. Sometimes FeMn crusts are covered by a thin layer of calcareous sediment, which would be removed during mining, and the suspension and redeposition of sediment could have a similar, though much smaller impact than in the case of Mn nodule mining. Because deep-sea fishing is now also protruding into the open ocean and seamounts have become targets for fishing, negative synergies and potential conflicts with deep-sea fishing, especially trawling, could occur (see, e.g., Koslow et al. 2001). Although the impacts of mining FeMn crusts on seamounts and fishing by trawling cannot be compared directly because fishing usually takes place in areas with much higher bio-productivity, the direct removal of surface substrate may have similar effects for sessile organisms. Return visits to former sites of bottom trawling operations off the coast of Australia and New Zealand (Williams et al. 2010), as well as dredging sites on the Corner Rise seamounts (Waller et al. 2007) show that disturbance tracks remain visible even after 10 and 30 years, respectively. This indicates that disturbance created by FeMn crust mining also will last for a very long time and that the habitat community composition will be different, even if recolonization of the affected sites takes place. Whereas the removal of crusts will cause a long-term or permanent destruction of the seafloor, the magnitude and duration of impacts in areas affected by the particle plume will depend on the biodiversity and resilience of benthic communities, as well as local oceanographic conditions. Most organisms at seamounts are long-lived and reproduce very slowly. Hence, organisms showing a faster regrowth may dominate the disturbed system for a long time.

3.1.3 Seafloor massive sulfide deposits

SMS deposits generally serve as habitat for a community of hydrothermal vent species that inhabit active deposits and a community of periphery fauna that inhabit inactive deposits (Van Dover 2004; Van Dover 2011). Hydrothermal vent fauna is usually characterized by high biomass and low diversity (Grassle 1985). Many of these species are endemic and depend on a functioning symbiotic relationship with the chemoautotrophic organisms that typically inhabit these active hydrothermal systems (Childress and Fisher 1992). The peripheral fauna is typically similar to seamount fauna and is composed of sessile, long-lived, slow-growing and filter-feeding taxa such as sponges, corals, anemones, and holothurians (Van Dover and Hessler 1990; Galkin 1997; Collins et al. 2012).

The removal of SMS deposits results in habitat loss, which in turn affects sessile benthic fauna. Although the chimneys (vertical edifices) do re-form in actively venting areas, mining could influence the distribution of venting activity within a radius of up to hundreds of meters (Van Dover 2011). Active hydrothermal vent systems rise and fall on timescales of months to centuries, although there seems to be a difference between fast-spreading ridges, such as the highly dynamic East-Pacific Rise, and slow-spreading ridges, such as the Mid-Atlantic Ridge, with its longer-lasting phases of individual hydrothermal activity (Rona et al. 2010). Recolonization on actively venting areas happens comparatively quickly within a period of several years and largely resembles the original composition (Tunnicliffe et al. 1997). The ecosystem of an active vent field would also naturally collapse within a few years, once the active venting stops. Mining would, however, only rarely take place in actively venting areas but mostly in extinct inactive vent sites where deposit formation has come to an end. Ridges and inactive vents will take longer to recover because they resemble the ambient deep-sea environment, where all biogeochemical and biological processes occur very slowly (Williams et al. 2010). In fact, Boschen et al. (2016) highlight that even if habitat is available after mining, it may still take centuries for mature corals and other species to recolonize the area. It is likely that the fauna that has settled on inactive vents after the extinction of active venting would be destroyed. Identifying inactive vents for mining may be difficult because distinguishing between those and merely dormant vent fields is challenging.

The impact of mining SMS deposits will be site specific for several reasons. Firstly, each active vent site has a unique composition of the community, which is a direct reflection of the specific geologic, physical, and chemical conditions of the fluid emitted at the site and the maturity of the venting system. Benthic hydrothermal organisms differ with respect to ecological characteristics, including mobility, dispersal, feeding strategies, and trophic interactions. Secondly, benthic organisms show a distinct zonation in relation to the distance from the vent. This zonation varies for every hydrothermal vent site (Arquit 1990). Thirdly, the spatial and temporal scale of impacts varies widely between vents. Lastly, the nature and magnitude of the plume impact will depend on the mining technology and equipment used. The response of the benthic community to these impacts will thus also be site specific, which affects the reliability of predictions and the design of potential mitigation measures. In light with this, Boschen et al. (2016) point out that megafaunal assemblages in active vent areas are highly site specific, indicating that locating areas that comprise an almost identical community composition, and that can therefore serve as corresponding preservation areas, will be challenging. However, the areas affected by SMS deposit mining would be small compared to those of FeMn crust mining, and especially Mn nodule mining, so the environmental impacts can, in this case, be estimated to be much smaller on both temporal and spatial scales.

3.2 Geochemical impacts

3.2.1 Manganese nodules

Besides direct biological impacts, deep-sea mining can also lead to geochemical changes, including the alteration of the chemical equilibrium of the sediment-water interface due to Mn nodule extraction (Koschinsky et al., 2001). Experimental studies indicate a release of potentially toxic metals from the sediment and porewaters, the extent of which is, however, expected to be limited as long as the chemical balance at the interface remains essentially undisturbed. Nonetheless, a strong interference may occur in areas where the penetration of O into the sediment is very low or where collectors are causing a particularly deep disturbance. The exact type and degree of geochemical impacts will be site specific and is dependent on the technology used. Recent investigations in the German license area for Mn nodule mining in the CCZ, for example, show that the O penetration depth is greater than 1.5 m (Mewes et al. 2014), which reduces the likelihood of a massive reduction in O content and subsequent dissolution of the metal-rich Mn oxide phase causing the release of heavy metals.

Although the O penetration depth varies even within the CCZ, current knowledge of the area indicates a sufficient oxygenation of the surface sediment in the entire area so that a reduction of Mn and Fe oxides with release of toxic trace components would not be expected. In the Peru Basin, where the DISCOL experiment had been carried out and which is another prime location for Mn nodules, the situation is completely different. The Peru Basin is characterized by an oxic sediment layer of just 5 to 10 cm and is suboxic below this depth. Because the metal-bearing Mn oxides are not stable under suboxic conditions, the metal-ion concentration in the sediment porewaters is higher, and a disturbance of the topmost 10 to 20 cm of the sediment could lead to a measurable direct release and subsequent diffusion of the metals into the bottom water (Fritsche et al. 2001). However, given that the ISA has not awarded exploration licenses for this area, there is no commercial mining activity expected to occur in the Peru Basin in the near future.

3.2.2 Ferromanganese crusts

The extraction of FeMn crusts would likely not be associated with the release of toxic metals, unless mining were to occur in particularly shallow waters in the O minimum zone (500 – 1,000 m or even 500 – 2,000 m, depending on the ocean region), where metal-release processes could potentially occur. However, because the O minimum zone is usually not very pronounced at seamounts with FeMn crust growth, which is a prerequisite for their formation (Koschinsky and Halbach, 1995) (i.e., O values are still in the oxic range), a significant release of metals is still not expected.

3.2.3 Seafloor massive sulfide deposits

Because both dissolved and particulate metal concentrations are by nature very high in active hydrothermal vent systems, no significant additional toxic effects or other geochemical imbalances would be expected in the case of mining SMS deposits. Hydrothermal organisms have been shown to carry a rather high body burden of metal in their tissues, which is a direct reflection of their metal-rich environment, and they seem to have developed adaptation strategies to mitigate potential toxic effects (Koschinsky 2016).[2]

3.3 Impacts in the water column

Impacts occurring in the midwater column arise from the vertical transportation of the mined minerals or the potential input of discharge water and sediment from the support vessel (SPC 2013b; SPC 2013c; SPC 2013a). Whereas the mineral material will be transported to shore, the separated seawater could be discharged at sea on the surface, close to the seafloor, or somewhere in the water column. The physical properties of the discharge water (e.g., salinity, metal and nutrient concentrations, and temperature) may differ from those of the ambient seawater. If the discharged water were to be released in the topmost 200 m, it could affect primary productivity by reducing light penetration or introducing nutrients or toxic chemical content. The creation of a particle plume could also cause localized O depletion (ECORYS 2014). Hence, return of the particle-rich waters into deeper parts of the ocean, preferentially close to the seafloor, is recommended. Also, the impact of sediment plumes caused by the seafloor activities may extend much further than the mining site due to transportation of the material with the currents (SPC 2013a), which means that good knowledge of the water-mass movements and currents in the mining area are required to minimize plume spreading. Former studies on the spatial and temporal distribution of the sediment plume mostly used hydrodynamic models on different scales to predict the fate of the plume (Jankowski and Zielke 2001; Rolinski et al. 2001). Experimental investigations on larger scales are basically missing for the fate of sediment and ore particles released during the mining process. In the models, the particles have largely been considered as conservative components that do not change with time, and possible aggregation effects, which are typically observed under such scenarios (e.g., Thomsen and McCave 2000), have been neglected. The results of the earlier studies may have potentially overestimated the range of the particle distribution because larger particle aggregates would settle faster than the models have assumed.

[2] More recent research indicates that vent fauna may, in fact, be affected by geochemical impacts of deep-sea mining (see Chapter 5).

Resuspended or discharged particles in the water column may influence microbial activities because they could serve as additional nutrient sources, which may potentially lead to the microbial reduction of Mn and Fe oxides form the particles. Microbial matter, however, may also act as a kind of glue, enhancing agglomeration of smaller particles, and hence increase deposition rates of the suspended matter. Up to now, these processes have not been studied to a great extent and should be included in future deep-sea mining impact studies.

The removal of FeMn crusts or SMS deposits would typically not be associated with the formation of a sediment cloud because of the lack of thick layers of sediment on the slopes of seamounts and in the geologically very young environments typical for SMS formations. However, discharge water could still contain abraded metal-rich particles from the crusts or sulfides, which could be ingested by organisms or, especially in the case of SMS deposits, particles would release metals into the water and should, therefore, also be discharged into deep waters.

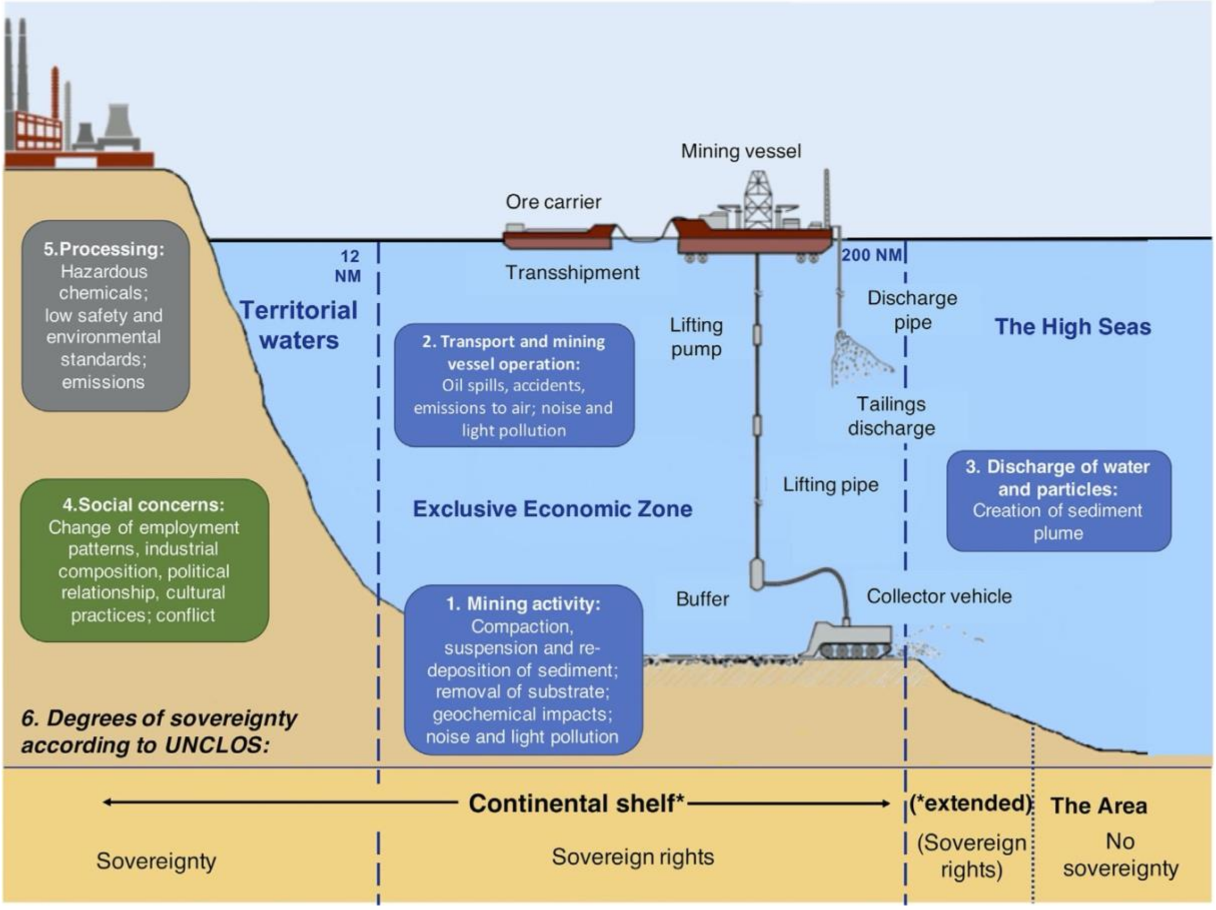

Figure 6: *Sketch showing the environmental and social concerns associated with the mining operation (blue), the processing of the mined material (gray, not covered in the present article), and on land (green) in the context of maritime zones as defined by UNCLOS (Reprinted from Koschinsky et al. 2018).*

4 Comparison to environmental impacts of terrestrial mining

While deep-sea mining will certainly be associated with adverse environmental impacts, it may still turn out to be the preferred alternative to terrestrial mining, given an effective and efficient implementation of environmental regulation and monitoring of compliance. To date, only very few direct comparisons of terrestrial and deep-sea mining exist, all of them taking different methodological approaches. Overall, thoroughly comparing terrestrial and deep-sea mining impacts is very challenging because the mining activities and environmental settings in the two systems are considerably different. In a recent study commissioned by Nautilus, Batker and Schmidt (2015) compared terrestrial and open-pit Cu mining sites to Nautilus' plans to extract SMS deposits in their Solwara 1 area in the EEZ of Papua New Guinea following an 'ecosystem approach.' Ecosystem services describe the direct and indirect benefits humans obtain from well-functioning ecosystems.

As stated in the Millennium Ecosystem Assessment (MEA 2005), ecosystem services can be subdivided into four categories:

1) Provisioning services, which describe the "products people obtain from ecosystems"
2) Regulating services, which are the "benefits people obtain from the regulation of ecosystem processes"
3) Cultural services, which include the "nonmaterial benefits people obtain from ecosystems"
4) Supporting services, which are those that are necessary to produce all the other services

In their study, Batker and Schmidt (2015) find that deep-sea mining appears to be an overall desirable alternative to terrestrial mining in all categories. In the case of provisioning services, deep-sea mining appears to be preferable to terrestrial mining with respect to nearly all services (e.g., food, medicinal resources, water supply), with the sole exception of 'energy and raw materials,' in which both terrestrial and deep-sea mining sites perform equally badly. In the category of regulating services, which, inter alia, includes 'climate stability, air quality, soil formation and retention, waste treatment and water regulation,' deep-sea mining activities seem to be the better option in all categories. In terms of cultural services, which include, for example, scientific and educational purposes, recreation and tourism, and spiritual and historic values, deep-sea mining also appears to be preferable. The same is true for the supporting services (e.g., habitat and nursery, nutrient cycling, and genetic resources), except for 'habitat and nursery,' in which the performance appears to be similarly bad for both forms of mining. Batker and Schmidt's (2015) analysis is criticized for, among other things, focusing on ecosystem services that are relevant to only terrestrial environmental settings but not to remote deep-sea ecosystems (Grey and Rosenbaum 2015).

In another study, McLellan (2015) uses the method of life cycle assessment (LCA) to compare Nautilus Minerals' deep-sea mining concept with the extraction of Cu from two underground Cu mines in Canada. Life Cycle Assessment, originally introduced in the 1960s, provides a comprehensive methodological framework to compare environmental impacts of a product or service throughout its entire life cycle (Rebitzer et al. 2004). First results of this study indicate that the mining of deep-sea mineral deposits appears to be more "energy and emissions-intensive than the average onshore deposit," and the impacts, overall, resemble those of deep onshore mines.

Hein and Koschinsky (2014) take a more qualitative approach and conclude that deep-sea mining may be the preferable alternative because it does not require the same excessive preparation of terrestrial mining sites, which often includes the deforestation of large areas and the dislocation of local inhabitants from ancestral land. Furthermore, nearly all terrestrial mines are accompanied by a substantial amount of mine waste. The deposition of thick overburden, which can account for up to 75% of the moved material, can also lead to significant environmental degradation. In addition to these foreseeable impacts, mines on land are often locations of severe accidents such as dam failures at mine waste disposal sites, which directly or indirectly affect ecosystems and communities. A prominent example of this is the collapse of the Fundão tailings dam close to Rio Doce in Brazil in 2016; the resultant release of roughly 50 million m^3 of mud and toxic sludge caused 19 deaths, the displacement of numerous families, and interruption of access to clean water and food for several hundred thousand inhabitants (Miranda and Marques 2016). Acid mine drainage, which can cause metal contamination in the vicinity of metal-sulfide ores mined on land, would not occur during the extraction of marine oxide minerals such as Mn nodules and FeMn crusts, and would be buffered by seawater in deep-sea sulfide mines. However, once retrieved from the seafloor, deep-sea mineral ores will need to be treated on land similarly to those retrieved from terrestrial mines. Because processing plants for the beneficiation and refinery of deep-sea resources do not yet exist and processing routes have not yet been tested on a commercial scale, it remains unclear which types and quantities of chemicals (e.g., acids, solvents) and other resources (e.g., energy, water, space) will be required and whether and to what extent their use will be associated with adverse consequences. Terrestrial mines also require the establishment of infrastructure such as roads and building complexes. In contrast, deep-sea mining largely relies on the use of movable infrastructure such as mobile collectors and ships. The mined material will be brought to a harbor from which it can be transported on existing roads. After the closure of one deep-sea mining site, the mobile structure can easily be removed and reused at another site. Moreover, the complete harvesting procedure would mostly be managed by vessels and mobile miners in the sea and, therefore, would not require the construction of large housing complexes on land (Hein and Koschinsky 2014; Petersen et al. 2016). However, any impacts from sea surface operations, including emissions by the mining and transport ships, which have mostly been disregarded so far, would have to be considered in an environmental impact assessment as well. Nevertheless, ensuring environmental impacts in the Area and minimum environmental and social impacts in EEZs in the context of deep-sea mining requires the development of appropriate legislation.

5 Legal aspects of deep-sea mining

Deep-sea mining activities are not taking place in a legal or institutional vacuum. A complex set of rules and institutions governs ocean activities such as deep-sea (Markus and Singh 2016). The starting point for all regulatory aspects on the oceans, including deep-sea mining, is the 1982 United Nations Convention on the Law of the Sea (UNCLOS). UNCLOS is routinely referred to as 'the constitutions for oceans' due to its comprehensiveness in regulating human activities at sea through the division of maritime zones and the prescription of applicable rights and obligations. One of its related instruments, the 1994 Implementation Agreement on Part XI of UNCLOS ('1994 IA'), is of particular interest because it operationalizes the UNCLOS provisions pertaining to deep-sea mining. The locations of the underwater mining sites determine how deep-sea mining is legally addressed, as well as who has the right to exploit resources and is ultimately responsible for minimizing adverse environmental impacts. Through UNCLOS, maritime zones have been designated that fall either within national jurisdictions or beyond them (Tanaka 2015) (Figure 6). In their territorial waters (which extend up to 12 NM from their baseline, or the mean low-water mark), coastal states enjoy sovereignty, just as they do over their territory on land (UNCLOS, Article 2). Coastal states can furthermore declare EEZs, which extend up to 200 NM from the baseline, in which they enjoy sovereign rights to exclusively exploit living and non-living resources (UNCLOS, Article 56 (1)). This zone is complemented by the continental shelf zone (in general also up to 200 NM from the baseline), where coastal states enjoy similar rights over resources on the seabed and the subsoil thereof (UNCLOS, Article 77 (1)). Unlike the EEZ, the continental shelf does not need to be declared by the coastal state (UNCLOS, Article 77(3)). It exists "as a right" of the coastal state for a distance of 200 NM, and it may be further extended to a distance of up to 350 NM or more, provided Articles 76 (4)-(9) of UNCLOS are met. This is particularly relevant for deep-sea mining because continental shelves are often locations with a high abundance of minerals. In cases where mining exploitation takes place in the extended continental shelf, Article 82 of UNCLOS prescribes that the "coastal state shall make payments or contribution in kind [to the ISA] in respect of [mineral] exploitation […] beyond 200 nautical miles […]." In areas within national jurisdiction, UNCLOS mandates coastal states to "adopt laws and regulations to prevent, reduce and control pollution of the marine environment arising from or in connection with seabed activities subject to their jurisdiction" (UNCLOS, Article 208). Although standards are being developed through the ISA to govern deep-sea mining in the Area, at present there are no specific international rules or standards pertaining to deep-sea mining in the EEZ or continental shelf. Thus, coastal states have the prerogative to regulate deep-sea mining activities within their maritime zones. It has been argued, however, that environmental standards developed in connection to the Area are international standards that are equally applicable to places under national jurisdiction (SPC 2013d). This argument is a subject of debate among scholars (Markus and Singh 2016).

In any event, it is a well-established principle under customary international law that states shall prevent transboundary harm arising from activities conducted within their jurisdiction. This is an obligation of conduct (also enshrined in UNCLOS) that requires coastal states to exercise diligence by taking measures to, inter alia, minimize pollution from vessels as well as from “installations and devices used in exploration or exploitation of the natural resources of the seabed and subsoil” (UNCLOS, Article 194 (2) and (3c)). Furthermore, customary international law also stresses that states require environmental impact assessments to be prepared within their jurisdiction. This duty is continuous and requires states to monitor the environmental impacts of ongoing activities within their jurisdiction (Pulp Mills on the River Uruguay…2010, para 204-205).

To this end, several states with vested interests in deep-sea mining within their areas of national jurisdiction have already established national laws to regulate those activities. For instance, the Cook Islands enacted the Seabed Mineral Act in 2009 and the Seabed Minerals (Prospecting and Exploration) Act in 2015, and Tonga enacted their Seabed Minerals Act in 2014. Currently, several countries, including Portugal, are in the process of developing their own legislative frameworks for deep-sea mining. Other countries have refrained from creating new legal documents but have instead integrated deep-sea mining into statutes dealing with offshore petroleum activities in their waters. This includes, for example, New Zealand’s Exclusive Economic Zone and Continental Shelf (Environmental Effects) Act of 2012 and Papua New Guinea’s Mining Act of 1992.

In Areas beyond national jurisdiction, deep-sea mining activities are governed through the ISA, which is currently in the process of preparing the necessary regulatory framework. This includes the production of a comprehensive Mining Code, covering all three mining stages in the Area – prospecting, exploration, and exploitation – and subjecting each of them to specific environmental requirements (Lodge 2015). One important precondition to carry out exploration or exploitation activities in the area is that interested entities, if not a member State themselves, must first obtain sponsorship from a state that is Party to UNCLOS. This is an essential arrangement that entails significant consequences under international law. By agreeing to sponsor an entity, a state undertakes to meet several obligations. These obligations include the duty to assist the ISA in exercising control over activities in the Area; to apply the precautionary approach, a strategy for coping with potential environmental impacts even if their causes and effects are not yet understood or scientifically verified (Kriebel et al. 2001), to implement best environmental practices, and to conduct EIAs. Failure to exercise due diligence in meeting these obligations could attract responsibility under international law on the part of the sponsoring State (ITLOS 2011).

With respect to prospecting and exploration, the Mining Code comprises three distinct sets of regulations, the first one covering Mn nodules (2000, revised 2013), the second one SMS deposits (2010), and the third one FeMn crusts (2012). All three sets are generally similar in terms of scope and content and are differentiated mainly to address the unique spatial and geological characteristics of the respective type of deposits (Lodge 2015). The three sets of regulations are collectively termed the 'ISA Regulations on Prospecting and Exploration.' In addition, the ISA, most notably through its Legal and Technical Commission (LTC), may issue recommendations from time to time with which contractors are expected to comply 'as far as reasonably practical' (Lodge 2015). One important recommendation is the 'Recommendation for the Guidance of the Contractors for the Assessment of Possible Environmental Impacts Arising from Exploration for Marine minerals in the Area' (ISBA/19/LTC/8), which applies to all three types of mineral deposits. This instrument requires contractors to collect and submit data on the baseline conditions in the exploration area using the best available technology, to prepare and submit prior environmental impact assessments for activities such as drilling and rock sampling, to prepare and submit reports during and after the performance of specific activities, and to engage in a cooperative relationship with other oceanographic disciplines to close knowledge gaps.

As for exploitation activities, regulations are currently being drafted and will ultimately feature as part of the Mining Code. The 'Revised Draft Regulations on exploitation of Mineral Resources in the Area' (ISBA/24/LTC/WP.1) were released by the LTC in June 2018 and are currently (as of July 2018) at an advanced stage of receiving and considering stakeholder feedback. The revised draft covers some essential aspects of the governance process with respect to the application and approval process for a plan of work, salient terms in a contract for exploitation, matters of environmental concerns (such as requirements to prepare a feasibility report, an environmental (and social) impact statement, a mining plan, a financing plan, an emergency response and contingency plan, a training plan, an environmental management and monitoring plan, and a closure plan), inspections, enforcement, and settlement of disputes. It is expected that substantial effort will be undertaken toward finalizing the draft on exploitation in the near future, after which it would be known as the 'Exploitation Regulations.'

Finally, the special legal status of the seabed in the Area deserves some attention. The non-living resources on the deep seabed in the Area have been declared as the 'Common Heritage of Mankind' (CHM) in which exploitation shall be carried out for the benefit of all humankind (UNCLOS, Article 136). Essentially, these mineral resources are treated as a common good, which requires responsible management by one common institution with global representation, namely the ISA. This process of management includes the development of a single regime that governs the exploration and exploitation of the mineral resources, as well as the equitable allocation of benefits arising therefrom. With respect to the payment mechanism framework, the ISA would have to ensure that the regime it creates allows equal participation while abiding by the concept of distributive justice regarding the allocation of benefits from the exploitation of deep-sea minerals. The concept of distributive justice has not been fully defined in this context, and it is unclear how the distribution of benefits might occur. Although developing countries have expressed their expectation of equal distribution of mining wealth, developed countries indicate that they expect the mining countries to pay remittances to the ISA (Fritz 2015).

Efforts are currently being undertaken at the ISA to develop a payment mechanism system that is reflective of the CHM principle. It is expected that in setting the parameters of the benefit-sharing arrangement, the payment mechanism should incorporate notions of fairness, transparency, accountability, and inclusiveness (Jaeckel et al. 2016). Furthermore, good governance and responsible management also obligates States and their sponsored entities engaging in those activities to not only protect the marine environment and prevent serious harm to the seabed (Levin et al. 2016), but also to ensure that the resources are harvested and utilized in a sustainable manner, taking into account the needs of future generations to access and utilize these resources (Joyner 1986; Baslar 1997; Wolfrum 2012). However, these themes are also subjected to their own debates; for instance, what amounts to 'serious harm to the marine environment' from seabed mining activities is in itself a topic of contention (see Levin et al. 2016) and requires a thorough understanding of the special characteristics of deep-sea ecosystems and the spatial and temporal scales of the complex interactions within these systems.

6 Economic considerations of public and private actors

6.1 Uncertainties associated with deep-sea mining

Despite early research efforts, deep-sea mining was deemed economically unfeasible in the 1980s, and until its resurgence in the 2000s, most exploration activity had ceased due to decreasing commodity prices and a lack of appropriate extraction and processing technology. However, despite advancements of companies such as Nautilus, UK Seabed Resources, Ocean Minerals Singapore, Marawa Research, and Nauru Ocean Resources, engagement by private companies is limited compared to land-based mining, albeit growing, with quite a few activities focusing on technology development and equipment building. Although mining for vast deposits of valuable metals seems like an attractive commercial opportunity, an array of uncertainties have kept large, multinational firms from the world's traditional mining centers in Western Europe, China, Russia, Australia, and Canada from becoming active on a large scale (ICMM 2012). High costs for initial investments in technologies, pilot mining tests, and environmental impact assessments are just two of the more visible concerns. Thus, for their long-term planning, mining companies must consider alternatives to deep-sea mining, such as the expansion of terrestrial mining, recycling, the development of suitable substitutes, and increasing resource efficiency, all of which may turn out to be far less cumbersome than retrieving mineral resources from water depths of up to 6,000 m (van Gerwe 2014). Other uncertainties relate to the types and locations of exploitable deposits, mining volumes, and resource potential (especially SMS deposits), as well as to the cost of exploitation and processing. Likewise, academic studies on the viability of deep-sea mining must accept numerous difficult-to-validate assumptions (ECORYS 2014). Basic predictions of long-term demand trends, which are important elements for determining price levels and, ultimately, the profitability of deep-sea mining, are necessarily based on error-prone assumptions about the development of worldwide income and consumption trends. In recent years, world metal prices surprised economists with their high volatility (Arezki et al. 2014). Moreover, translating environmental and social concerns into national and international regulations and harmonizing these laws will likely take many years. Although the ISA Council may come up with first conclusions by 2020, national regulations will take many years to emerge and discussions at the ISA will continue once economic, social, and environmental effects of deep-sea mining are going to present themselves (Markus and Singh 2016). Against this background of uncertainties, there are however also studies that shed a positive light on the profitability of deep-sea mining compared to land-based mining operations, specifically regarding the capital and operating expenditures in the case of Mn nodules (ISA 2008; Sharma 2011).

6.2 State involvement in deep-sea mining activities

Although commercial activity is currently limited because of the numerous uncertainties associated with mining processes, the extraction of mineral resources from the deep sea is still of great economic relevance. After having been rather inactive for quite some time, states are currently taking an important lead in these early development stages of a potential global ocean economy by financing research and development (R&D), by starting to negotiate societal concerns vis-a-vis commercial interests, and determining legal frameworks that have a decisive influence on profitability of commercial undertakings. Experience from the Industrial Revolution shows that those states and firms that act as pioneers in the exploitation of new economic opportunities gain a strong strategic advantage in a world governed by steep learning curves, economies of scale and scope, and spillover effects (Robinson 1988; Krugman and Obstfeld 2003). Relying on a combination of R&D and cross-border commercial diplomacy, ocean economy plans such as the European Union's (EU) Blue Growth strategy, a long-term initiative to encourage growth in the EU's marine and maritime sectors, can be interpreted as the early but decisive stages of industrial policies aimed at creating international competitive advantages in domestic industries. These strategies not only attempt to secure access to critical raw materials for industrial production, as in the case of the REEs, but also to open new avenues for economic growth, job creation, and government revenues (EC 2012; Remotti and Damveraki 2015). Deep-sea mining is only one element of a much larger historical undertaking: the 'industrialization of the world ocean' (Smith 2000). If state actors are interested in paving the way for large companies to increase their commercial activities in deep-sea mining, they will need to make significant and risky investments for several years, if not decades. This leads to questions as to which states will take the lead and what conduct can be expected from them in the international commercial arena once the economic viability for exploitation is more predictable. Familiar questions and controversies will reemerge from the world economy, for example, concerning the different strategies of state-owned companies, private companies, and their home-country governments. Countries with a head start in deep-sea mining could be those that already have companies engaged in the extraction, processing, and trading of minerals obtained from terrestrial reserves. These firms' home countries seem to mostly coincide with those whose governments are active in exploration activities and involved in shaping corresponding legal discourses. For trading REEs, this involves, for example, Canada, USA, Australia, China, India, Russia, and Japan. Most of these countries, as well as France and Estonia, are also major players when it comes to the separation and processing of REEs (Massari and Ruberti 2013). Lastly, states that have minerals in and around their EEZs and continental shelves will likely play a decisive role in the 'global ocean economy' as well. This country group includes some of the Pacific Island States, such as Papua New Guinea and the Cook Islands (World Bank 2016).

7 Social concerns and impact management

Thus far we have discussed the environmental, legal, and economic dimensions of deep-sea mining; in this section, we examine the social impacts on humans. In general, social impacts are changes caused by any kind of interventionist activity, including mining, and can take myriad forms. For example, social impacts may be positive or negative, intended or unintended, direct or indirect (Franks 2011; Roche and Bice 2013; Vanclay et al. 2015). Examples include “employment effects, changes to social services such as health or childcare or the availability of cost of housing, and cultural change such as changes in traditional family roles as a result of the demands of mining employment, or even the breakdown of traditional economies due to the introduction of a cash economy” (Franks 2011: 1817) (Figure 6, impact 4).

Social impacts are also complex and cumulative. They occur across the entire life of a project and may change as a project moves from one phase to the next. They are also situation specific, meaning that communities contending with similar projects may experience vastly different social impacts. Indeed, different communities may be impacted differently by the same project. With regard to deep-sea mining, impacts might occur at near and far distances to coastal states’ shores (both in their territorial waters and their EEZs), and as some scholars contend, impacts may be also result from mining in the Area (Durden et al. 2018). For example, impacts might be caused by sediment plumes and could affect areas far beyond the mining sites; indeed, as marine scientist Andrew Thurber warns, the impacts of deep-sea exploitation, including mining, could be global (Floyd 2014).

Because social impacts can have serious deleterious effects, they need to be identified, and management plans should be designed before mining begins. Analyses identify and predict impacts by conducting a formal social impact assessment (SIA), which is typically part of a project’s EIA. Both the SIA and the EIA form the basis for the environmental impact statement (EIS). Like the EIA, the SIA should cover the entire life cycle of a project, from project identification and feasibility studies to construction and operation, through to project closure.

Recent guidelines for evaluating social impacts for any type of project, not just mining, specify a series of tasks that should occur in four overlapping phases:

1) “Understanding the issues” (including data collection, community profiling, and informing the community, as well as inclusive participatory processes)
2) “Predict, analyze and assess the likely impact pathway” (including identifying impacts and their significance”
3) “Develop and implement strategies” (including addressing negative impacts, enhancing benefits, community support, developing a Social Management Plan (SIMP)
4) “Design and implement monitoring programs” (including creating indicators to monitor change and participatory monitoring plan, evaluation and review) (Vanclay et al. 2015)

A core principle of SIAs is that impacted communities should be engaged and involved throughout the process. Because commercial deep-sea mining has hitherto not been undertaken, its impacts and implications can only be estimated. However, several scholars have made forays into researching potential social impacts, particularly in EEZs (Roche and Bice 2013; Rademaekers et al. 2015). For example, based on the social impacts ensuing from terrestrial mining, Roche and Bice (2013) have extrapolated several potential impacts of deep-sea mining. Specifically, they anticipate that deep-sea mining could influence where local scientists choose to work, and it could impose opportunity costs as the economy’s industrial composition changes. Political relationships could change, and conflict could emerge within communities between those who favor mining and those who oppose it. A government’s propensity for oppression may be altered if it attempts to suppress opposition to mining. Mining may also affect “access to marine resources” with “implications for subsistence or other local fishing operations, disruption of cultural practices or damage to culturally important coastal areas or deep-sea sites” (Gibson et al. 2011; Roche and Bice 2013). A different attempt at assessing the potential social implications of deep-sea mining in EEZs was undertaken by the European Parliamentary Research Service (EPRS) (Rademaekers et al. 2015), which conducted a ‘light’ cost-benefit analysis (‘light’ due to the lack of data) for both the EU and the communities located near the mining operations. The EPRS foresees deep-sea mining as generating few new jobs in the EU in comparison to terrestrial mining or recycling and creating a minimal number of jobs for local communities. However, the EPRS found that the costs of deep-sea exploitation for local communities could be substantial, for example if “fish stocks are affected, or land-based processing practices of mining related activities are not controlled” (Rademaekers et al. 2015: 55). Indeed, fishermen in Papua New Guinea, the site of Nautilus Minerals’ Solwara 1 project, have already been negatively affected by pollution from terrestrial mining and are “nervous about the possible impact of [deep-sea] mining on fish stocks” (Rademaekers et al. 2015: 76).

Concerns about the negative impacts on fishing extend beyond this one example; they pervade the literature on deep-sea mining.

As documented in recent articles about conducting EIAs and SIAs for deep-sea mining projects, in both EEZs and the Area, Nautilus' Solwara 1 project in Papua New Guinea's EEZ has been criticized by independent experts and local stakeholders alike (for details, see Durden et al. 2018; Filer and Gabriel 2018). In preparation for its first EIA, Nautilus Minerals was involved in community outreach and consultations, including almost a dozen hearings in seven locations, and engaged in several community development projects, including job training and providing academic awards (Nautilus Minerals 2018). Despite these efforts, Nautilus Minerals' project ran into stiff competition. Nautilus Minerals was accused of misrepresenting the level of community support at the hearings (Filer and Gabriel 2018). Indeed, several nongovernmental organizations (NGOs) that were involved in the hearings opposed rather than supported the Solwara 1 project. Other sources of opposition included several Papua New Guinea politicians and public servants (Filer and Gabriel 2018). Nautilus was also criticized for publishing its EIA after it received its environmental permit in December 2009 and not before, which stymied comments and feedback. An indigenous social movement, the Bismarck-Solomon Seas Indigenous Peoples Council (BSSIPC), engaged a marine conservation professor from the University of Alaska, Rick Steiner, to conduct an independent review of Nautilus' EIA. Among other criticism, Steiner (2009) concluded that the EIA underplayed the risks the Solwara 1 project would pose, and Steiner himself became an outspoken critic of the project. The BSSIPC published a formal document, the Karkum National Seabed Mining Forum Statement, which listed their objections and concerns about the Solwara 1 project, including the paucity of research, the absence of laws, and "the lack of any meaningful consultation regarding the effects of this mining activity." This latter complaint indicated that the "inclusive participatory processes," which should be an integral component of any EIA or SIA, were not perceived as adequate. Overall, the BSSIPC concluded: "we do not consent to the seabed mining activities in our waters and seas" (BSSIPC 2008). By withholding consent, the BSSIPC was in effect questioning the project's legitimacy.

Legitimacy is precisely what any type of interventionist project needs in order to obtain a so-called 'social license to operate,' a term used in the onshore mining industry to refer to community sanctioning and tacit acceptance of mining operations. Although a 'social license' has no formal legal standing, the failure to achieve and maintain acceptance from key stakeholders can have "very negative implications for a mining operation" (Mason et al. 2010: 1347). Obtaining a 'social license to operate' for deep-sea mining operations will be difficult because it might not be clear which communities will be affected by the mine or how they will be affected. Indeed, after the initial negative reception of its Solwara 1 project, Nautilus went to great lengths to attempt to identify the communities that will be impacted and has created a 'Coastal Area of Benefit' (CAB) of the regions closest to the mining locations, comprising 22 villages and about 8,100 people (Nautilus Minerals 2018). Concomitantly, it reinvigorated its wider community engagement, reportedly reaching 30,000 people (Davidson and Doherty 2017). Nautilus has also begun direct negotiations with CAB communities and has established a development fund (Filer and Gabriel 2018). Since 2013, Nautilus Minerals has launched or increased educational and health programs along with other community development projects, and in 2015, it conducted a community needs assessment (Nautilus Minerals 2018). Nautilus, it seems, is on a learning curve.

The difficulties Nautilus has had in obtaining a 'social license' in an EEZ, and in identifying impacted communities, raises questions about how companies might obtain a social license in the Area or whether they will have to at all. However, there would certainly be stakeholders who would play a role in the project's review process. A recent assessment of the EIA process for deep-sea mining in the Area notes that stakeholder review is an element of EIA and that, for the Area, stakeholders would include "non-state actors such as environmental groups, other resource users (e.g. the fishery sector), proponents of other human activities occurring in the same space (e.g. tourism, shipping or cables), and the public as well as scientists and other experts" (Durden et al. 2018: 198). The authors also emphasize the high degree of uncertainty surrounding deep-sea mining policies. Thus, on the one hand, companies mining in the Area may confront an exacerbated version of Nautilus' conundrum (Are there affected communities? Who are they?), or companies may be in the position of not having to obtain a 'social license' if they can demonstrate there are no impacted communities. As Nautilus discovered, just because the mining site is offshore, this does not mean a company can dispense attaining a 'social license.' Without a 'social license,' a project's legitimacy might always be questioned.

In recent years, scholars have begun investigating the interrelationship between technology, justice (and legitimacy), and the core question of who benefits and who suffers particularly with regard to environmental issues (Smith Stegen and Bargu 2015). Whether new technologies, industrial facilities, or other types of projects are accepted, or, in mining parlance, obtain a social license to operate, hinges on various factors, including whether impacted groups consider procedures and outcomes as fair. From the justice literature, at least two pathways have been identified for securing legitimacy and thereby acceptance: 1) distributive justice (output legitimacy) and 2) procedural justice (input legitimacy). Both the distributive and procedural justice concepts are embedded in the SIA process, particularly in the Social Impact Management Plan (SIMP), which should be part of the third phase of any SIA. Social management plans delineate how negative social impacts should be avoided or ameliorated and how positive impacts can be enhanced (Franks 2011; Franks and Vanclay 2013). Unfortunately, the 'management aspect' of the social impact process is less developed than is the analytical and predictive framework. For affected communities, however, the management of social impacts is extremely important. This is clearly an area in which further research and investigation must be conducted. To attain output legitimacy, terrestrial mining companies often engage in 'benefit sharing,' such as providing employment and training, local procurement, infrastructure development, direct community investment, payments to the government, and compensation. It is worth noting that compensation can be thought of as the overarching concept or, as the World Bank categorizes it, compensation is one of several channels through which the benefits of a mining project can be shared. According to the World Bank, compensation from mining "refers to payments or other benefits (such as housing, in case of resettlement) provided by companies to affected communities to compensate for economic, social, environmental, or cultural damage directly caused by the mining operation" (Wall and Pelon 2011: 4). In tangible terms, companies might provide impacted communities with compensation via access to electricity and potable water supplies and might build infrastructure such as roads, schools, and hospitals. For companies, the 'benefit sharing' may be part of their corporate social responsibility (CSR) practices. Other less direct forms of benefit sharing can also include payments from companies to local or national governments, which in turn, are expected to redistribute the benefits and/or establish long-term redistribution mechanisms. For deep-sea mining, similar compensation practices could be followed, as manifested by Nautilus' recent attempts to gain a 'social license.'

It should be noted, however, that compensation plans are often plagued by two significant problems: corruption and transparency. Laws are often unclear on how money paid to governments should be redistributed, and anecdotes abound of missing or meager redistribution (Kimani 2009). Another issue is that offers of compensation do not always result in consent (Gallagher et al. 2008). It is sometimes difficult to derive a compensation calculation that is considered fair by all parties (Dietz et al. 1998). Furthermore, compensating for cultural impacts is often seen as critical because it is challenging and usually perceived as inappropriate to place monetary values on cultural assets (Gibson et al. 2011). However, compensation (distributive justice) is only one option for obtaining approval for a project. An alternative, or additional, pathway for companies or states to obtain project approval is through input legitimacy (procedural justice), which means that stakeholders and communities are allowed to play a role in decision making (Creighton 2005).

For community engagement to be meaningful, and to be perceived as such by the participants, certain conditions must be fulfilled, including:

1) The purpose of the participation must extend beyond information sharing
2) The public must be able to influence decision making to prevent it from being a sham
3) All relevant actors must be included
4) The public's participation must become part of the process early enough that it can influence outcomes
5) The public's participation must be intensive rather than shallow (Dietz et al. 1998)

Community participation and engagement are considered essential components of SIAs and impact management, so they should be deployed by companies or states that undertake deep-sea mining. Indeed, lack of involvement was one of the major complaints lodged by the local communities opposed to Nautilus Minerals' Solwara 1 project in Papua New Guinea. Nautilus Minerals has since become more active and its experience, a learning curve, will be instructive for other mining companies. In addition to gaining approval via compensation and participation, there are other ways of obtaining or increasing legitimacy, which will be discussed in the next section on public perceptions.

8 Public perceptions of and attitudes towards deep-sea mining

To understand the stakeholders' and communities' sense of legitimacy in relation to deep-sea mining, it is important to look closely at the basis of public perceptions and attitudes on the topic. Very little research is concerned specifically with public perceptions of deep-sea mining. In one study, Mason et al. (2010) used interviews and focus groups to explore industry and community reactions to the possible development of deep-sea mining in Australia. Specifically, in a dialogue process, stakeholders were asked to react to the term 'seafloor exploration and mining' in general to consider "exploration of bulk sands and gravels (aggregate) on the inner continental shelf (occurring at water depths of approximately 40-70 m)" (Mason et al. 2010: 1375). Whereas industry representatives emphasized economic benefits and a potential for environmentally sound mining, the possibility of seafloor exploration and mining was met with overall negative feelings among the community, NGOs, and other marine users. The latter perceived the marine environment as more sensitive and "fragile" than the terrestrial environment; they cited the negative consequences of onshore mining as a frame of reference and expressed lack of trust in the industry and decision-makers. Despite those concerns, many stakeholders in Australia remained open to the idea of seafloor exploration and mining, highlighting the need for further information on associated costs and benefits. In the absence of empirical knowledge, one can draw on insights form established theories and prior findings on perceptions and attitudes toward related issues, such as land-based mining or other marine issues (e.g., fishing), as well as other ‘macrosocial’ issues that people have been confronted with (e.g., promises and risk associated with nuclear power or problems of climate change) (Boehnke et al. 1993). These insights can sensitize us to potential problems or issues arising from deep-sea mining activities and help us derive concrete suggestions as to how legitimacy may develop. For example, narrative or social accounts that explain why a certain technological or infrastructure project must take place may be more effective in increasing legitimacy if they resonate with how the public already understands or represents the use at hand, as well as the actors involved (Farrell and Goodnight 1981).

People make sense of new developments in society (e.g., new scientific theories, technological innovations, here: deep-sea mining) not based on objective characteristics of the change process itself; rather, they apprehend new concepts through the lens of pre-existing knowledge structures that are perceived as being related and relevant to the new developments (see Bauer and Gaskell 1999; Wagner and Kronberger 2001), and react based on prior emotional and behavioral experience with change events that are perceived to be similar in their stress potential (Boehnke et al. 1993). To facilitate understanding, complex or abstract new phenomena are also often turned into something concrete and graspable (a process called ‘objectification’), for example, through being connected to a vivid image (e.g., an oversized tomato in which something is injected with a syringe, in the case of genetically modified food) (Wagner and Kronberger 2001). As a result, public understandings of new phenomena, especially in the beginning, may appear overly simplistic, illogical, or false, to the extent that they have been influenced by perceived risks and benefits, or worries and hopes, anchored to insufficient or inappropriate pre-existing knowledge or experience.

With regard to deep-sea mining, of which relatively little public awareness exists to date, it will be important to understand what knowledge it will be anchored to: terrestrial mining (see Mason et al. 2010), oil or gas extraction, fracking, etc. In each case, public attitudes towards deep-sea mining would be connected to different bodies of knowledge and images. Terrestrial mining, for example, is often objectified by images of huge areas of degraded land (as one can see when search for ‘land mining’ through Google Images). Furthermore, public attitudes toward deep-sea mining are also likely to depend on representations of the ocean. In a comparative study across different European countries, Potts et al. (2011) showed dramatic differences in the value attached to the oceans in various ways (e.g., weather and climate, source of food, producer of energy, recreation and tourism, etc.). In the Pacific Islands, the ocean may be valued as a spiritual heritage and common good that connects people and as something that is not distinct form the land (Mari and Kaschinski 2016). Also, trust in the actors that are or may become involved in deep-sea mining (e.g., multinational corporations, governments) is an important factor to consider (Mason et al. 2010). Pacific Islanders might even link deep-sea mining to such destructive foreign activities as the nuclear weapons tests in the South Pacific Ocean from 1946-1995 (Mari and Kaschinski 2016).

In addition to prior events or pre-existing bodies of knowledge that are perceived to be related to deep-sea mining, public perceptions and reactions are also likely to depend on more general values or orientations of individual and communities. It is likely that values and attitudes concerning the relationship with the natural world will play a role (Milfont and Duckitt 2010). To use Schwartz' (1994) terminology, value preferences that emphasize harmony with nature are likely to be associated with rejection of deep-sea mining endeavors wherever they take place, whereas preferences for mastery over the natural environment might encourage public legitimacy and cooperation. Furthermore, according to cultural theory of risk (Douglas and Wildavsky 1982; Rippl 2002), any environmental risk brought about by technological change is assessed by people in light of the degree of their grid (i.e., their willingness to accept hierarchy and to be restricted by rules) and their group (i.e., the relationship to other people and social units; fit in or stick out). Douglas and Wildavsky (1982) proposed four cultural types of risk assessment resulting from the interaction between grid and group:

1) People with an individualistic world view (low grid, low group) are concerned with individual freedom and will tend to see risk as an opportunity
2) Egalitarians (low grid, high group) are concerned with social equality and will tend to reject intervening technologies that might alter the natural environment
3) People with hierarchical cultural views (high grid, high group) conform to expert knowledge and will accept only those new technologies that are justified by an authority
4) Fatalists (high grid, low group) may be indifferent to risks due to lack of perceived control

Guillaume and Charron (2000) applied lessons from cultural theory to identify dimensions of risk perceptions related to waste from mining and milling U ore in France, which, in the absence of studies on deep-sea mining, may be indicative of the possible perceived risks and support for deep-sea mining across cultural prototypes. They emphasize, among others, dimensions such as perceived uncontrollability and long-term effects of mining threats, which may vary between individuals and cultures along the group axis; dimensions representing trust in governmental and scientific institutions, which are relevant for the grid axis; and dimensions related to benefits and advantages in the social management of the mining sites, which are expected to be salient among individualists.

9 Interdisciplinary cooperation in deep-sea mining research

The previous sections outlined the economic, environmental, social, and legal concerns associated with different process steps in the deep-sea mining value chain and demonstrated that deep-sea mining is a complex issue that must be approached from various disciplinary perspectives. For example, ensuring that a deep-sea mining operation is carried out as sustainably as possible, requires a thorough assessment of all possible impacts prior to the start of commercial operations, and ideally is based on input from different research fields, such as the natural and social sciences, such as political science as well as economics, engineering, and law. The cooperation among disciplines can be multidisciplinary when individual disciplines work separately on different process steps along the deep-sea mining value chain. However, closer, interdisciplinary cooperation regarding marine topics is often necessary (Markus et al. 2017). Interdisciplinary research is a style of research that integrates perspectives, methods, concepts, information, and data from at least two disciplines to advance the fundamental understanding of problems and develop adequate solutions (NAS 2005). Integrating ideas and tools usually restricted to one discipline can provide "conceptual and practical advances resulting from the synergy of different perspectives and contributions" (Khagram et al. 2010: 388).

With respect to the actual marine mining process, close cooperation among disciplines such as geology, geochemistry, oceanography, geophysics, and biology can, for example, substantially improve the exploration for deposits. Combining traditional geological exploration methods with geophysical tools such as seismic and electromagnetics can help identify extinct sulfide deposits and determine their vertical extension into the earth. Furthermore, joint research by biologists, geochemists, and oceanographers aids the quantification of anticipated habitat destruction, the release of heavy metals or other toxic elements, and the assessment of the creation and dispersion of sediment plumes in the water column and their impact on different types of organisms. Moreover, cooperation between scientists and legal practitioners is required to ensure that the environmental regulations in the Mining Code are based on meaningful threshold values.

Many past deep-sea mining research projects were carried out jointly by scientists of different academic backgrounds. Studying marine mineral deposits and potential environmental impacts usually requires research cruises, which are often very costly and cover more topics than can be addressed by representatives of a single discipline. Moreover, joint research is considerably more efficient because samples need to be retrieved only once, they can be shared by different research groups. For example, the Joint Programming Initiative Healthy and Productive Oceans (JPI Oceans) Action 'Ecological aspects of deep-sea mining,' which comprises a range of European research institutes, aims to jointly assess the long-term ecological consequences of mining and predict its ecological, biogeochemical, and hydrodynamic consequences, thus providing information for the development of an international regulatory regime. Moreover, the project intends to improve current assessment methods and monitoring techniques and to conduct comparative baseline studies across different deep-sea environments and to support and advise the ISA in the development of the Mining Code (JPI-Oceans 2014).

The MIDAS project brought together more than 30 organizations including research institutes, universities, small and medium enterprises, and industry partners. The project comprised expertise in geology, geochemistry, biology, biogeochemistry, oceanography, engineering, marine policy, and legislation. Jointly, the project partners worked toward identifying, analyzing, and evaluating potential adverse effects of deep-sea mining, as well as their magnitude and duration (MIDAS 2013). In contrast to MIDAS and JPI Oceans, the EU-funded 'Breakthrough Solutions for Mineral Extraction and Processing in Extreme Environment: Blue Mining' (Blue Mining 2014), which ended in 2018, was industry-led. Blue Mining consisted of nearly 20 large industry and research organizations with expertise in various fields of marine and maritime topics that aimed at significantly improving the sustainability performance of commercial deep-sea mining operations. Strong ties to industry remain particularly important for the development and conduction of a pilot mining test, which will aim at testing technology in-situ and monitoring the surrounding ecosystem before, during, and after the demo-project (Blue Mining 2014). However, in most of these previous studies, social sciences have not been involved to a significant degree, which indicates a gap in social assessment research related to deep-sea mining.

The cooperation within these projects appears to be beneficial to the project partners because it broadens their disciplinary perspective on individual topics and encourages mutual learning. By consulting representatives from other disciplines, it is possible to identify problems that otherwise would not have been considered. This approach is in line with the work of Rylance (2015), which highlights that interdisciplinary cooperation efforts "benefit single disciplines, extending their horizons." Moreover, it supports the establishment of efficient mechanisms of knowledge transfer and data sharing among academia, industry, and authorities. In addition, it reduces fragmentation and duplication of research (JPI-Oceans 2014). Interdisciplinary cooperation is likely to become even more relevant when cumulative impacts are to be considered because deep-sea mining will add to existing threats to the marine environment, including temperature increase, acidification, deoxygenation, and fishing (Markus et al. 2017). For understanding the complexities of the whole project, transdisciplinary research as a team in which scientists contribute their unique expertise while working outside their own discipline may in fact be an even better option.

10 Conclusion

The interest in deep-sea mining as a form of resource exploitation has only recently resurfaced; its short and long-term impacts on the environment, the economy, and human coastal communities as well as on society at large remain largely unknown. It is a highly complex issue characterized by a variety of economic, social, environmental, legal, and technical concerns. To date, it is mainly states and governmental institutions that are taking the lead in paving the way for future deep-sea mining activities. Private investment is largely absent due to substantial uncertainties associated with future metal demand and price trends, appropriate mining technology, and the social and environmental impacts associated with deep-sea mining activities. Overall, knowledge remains limited on the potential short and long-term ecosystem impacts in the deep-sea and it is currently difficult to reliably predict the effects of deep-sea mining on biodiversity and the geographical distribution of species. Concrete knowledge about the content and structure of emerging social representations of deep-sea mining in different countries is still lacking. However, the approaches described in the present paper can form a useful basis for understanding how individuals and societies might react to deep-sea mining activities, as well as for developing empirical research on public perceptions of and attitudes toward deep-sea mining.

Overall, opposition to deep-sea mining may arise from a myriad of actors: from local communities but also from remote communities and stakeholders, including social movements and concerned scientists. Their view of deep-sea activities may be moderated by their sense of associated justice and legitimacy. Because of the numerous uncertainties regarding deep-sea mining and its impacts, proponents must proceed cautiously and responsibly, and from the very beginning must identify and engage stakeholders in a transparent process. Engagement, however, is not an end unto itself but should be part of the process of managing and ameliorating impacts. The traditional ‘predict-and-prescribe’ approach seems insufficient to handle this degree of complexity. Instead, “research should integrate more closely with policy development to identify the range of alternative plausible futures and develop strategies that are robust across these scenarios and responsive to unpredictable ecosystem dynamics” (Schindler and Hilborn 2015: 953). To successfully approach the highly complex topic of deep-sea mining, natural and social scientists, as well as economists, legal practitioners, and engineers will need to join forces to incorporate the perspective of different disciplines early in the planning, exploration, and exploitation process. This not only ensures that all relevant disciplines are incorporated but also that linkages between the individual disciplines are identified and treated early in the research project.

With their considerable expertise in all relevant disciplines, the countries that have been active in the field of deep-sea mining research in the past decades are well poised to take a lead in conducting EIAs and SIAs, as well as in designing the framework for environmentally acceptable technology development. With the increasing global demand for metals on the world market and with deep-sea mining still being an activity of the future, such an interdisciplinary approach would help find solutions to any issues or concerns toward deep-sea mining through proper consultations and would help ensure that future actions consider sustainable development in the sense of the CHM.

Acknowledgement: Klaus Boehnke's contribution to this article was in part prepared within the framework of the Basic Research Program at the National Research University Higher School of Economics (HSE) and supported within the framework of a subsidy granted to the HSE by the Government of the Russian Federation for the implementation of the Global Competitiveness Program.

Disclaimer: The authors declare no conflict of interest.

Data Accessibility: All data are available through public sources.

Chapter 3: Quantification of emissions to air

Title of publication:

Quantifying the fuel consumption, greenhouse gas emissions and air pollution of a potential commercial manganese nodule mining operation

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Published in:

Marine Policy 114 (2020) 103678. DOI: https://doi.org/10.1016/j.marpol.2019.103678

The published article is available at:

Heinrich L, Koschinsky A, Markus T, Singh P. (2020). Quantifying the fuel consumption, greenhouse gas emissions and air pollution of a potential commercial manganese nodule mining operation. Marine Policy. 114:103678. doi:https://doi.org/10.1016/j.marpol.2019.103678.

https://www.sciencedirect.com/science/article/pii/S0308597X19300818.

Abstract

Manganese nodules contain economically valuable metals which may be mined in the future to supply metals to a growing world population. Thus far, environmental research has focused mainly on impacts occurring at the seafloor or in the water column but largely neglected impacts caused above the sea surface. Emissions of greenhouse gases and other air pollutants contribute to, inter alia, global warming, acidification, and photo- chemical ozone formation, which all negatively affect ecosystems and humans. We quantify the annual fuel consumption and emissions associated with a potential manganese nodule mining operation in the Clarion-Clipperton Zone with an annual production of three million tons (dry weight). We base the assessment on publicly accessible energy demand estimates from three different studies and complement this with a calculation of the fuel demand and emissions associated with transport scenarios to three different destinations. The global warming, acidification, and photo-chemical ozone formation potentials range between 82,600–482,000t CO_2-equivalent (-eq.), 1,880–11,197t SO_2-eq., and 1,390–8,734 t NO_x-eq., respectively, depending on factors including the engine loads, specific fuel oil consumption and transport speeds. We then discuss the regulatory dimension surrounding the topic. As three separate regimes (climate change, deep-sea mining, and international shipping) are applicable, we analyze the all three frameworks and provide an outlook for the future regulation of deep-sea mining-related greenhouse gas emissions.

1 Introduction

Marine mineral deposits like manganese (Mn) nodules, ferromanganese (FeMn) crusts and seafloor massive sulfide (SMS) deposits contain substantial amounts of metals, which serve as important raw materials for a variety of applications ranging from construction material to electronic devices and renewable energy technology (Mero 1965; Francheteau et al. 1979; Halbach et al. 1982; Hein and Koschinsky 2014). Deep-sea mining can take place in coastal states' territorial seas or exclusive economic zones (EEZs), or in areas beyond national jurisdiction ('the Area'), where no sovereignty can be asserted. As is the case with terrestrial mining, deep-sea mining will cause environmental impacts, which have already been thoroughly examined by various national and international multidisciplinary initiatives, such as the 'Deep Ocean Mining Environment Study' (DOMES, 1972-1981, Healy 1976), the 'Disturbance and Re-Colonisation Experiment' (DISCOL, 1989, Foell et al. 1990), the 'Japan Deep-Sea Benthic Experiment' (JET, 1994) (Fukushima 1995), the EU-project 'Managing Impacts of Deep-Sea Resource Exploitation' (MIDAS, 2013-2016) (MIDAS 2013) and the Joint Programming Initiative – Ocean's (JPI Oceans) projects 'Ecological Aspects of Deep-Sea Mining' and 'MiningImpact' (2015-2022) (JPI Oceans 2018). Until now, the environmental research focused mainly on impacts occurring at the seafloor, such as habitat destruction due to the removal of hard substrate and the suspension and re-deposition of sediment, as well as the creation of potentially far-reaching particle plumes in the water column (Giere 1993; Vanreusel et al. 2016; Koschinsky et al. 2018; Weaver et al. 2018). Impacts expected to occur above the sea surface, such as greenhouse gas (GHG) emissions and air pollution have been mostly neglected.

As widely agreed, upon, Mn nodule mining operations will consist of mining vessels from which the mining equipment will be deployed, as well as a number of bulk carriers or shuttle barges, which will transport the mined material to shore for further processing on land. The Mn nodules, which formed through the precipitation of metals from seawater and sediment pore water over the course of millions of years, are located in water depths between 3,500 and 6,000 m (Hein and Koschinsky 2014). They will be harvested by one or more collector vehicles and then lifted to the surface via a riser pipe. Onboard the mining vessel the Mn nodules will be washed, partially dried, and stored until they can be transshipped onto a transport vessel. The remaining sediment and seawater from the cleaning process will be discharged into the water column, preferably at near-seafloor depth (Agarwal et al. 2012; Blue Mining 2014; McLellan 2015; Ramboll IMS and HWWI 2016; Atmanand and Ramadass 2017).

On the high seas, hundreds of nautical miles (NM) away from the coasts, heavy fuel oil (HFO) is the most commonly used marine fuel in international shipping (Burel et al. 2013; McLellan 2015). The combustion of HFO, however, causes the release of GHGs such as CO_2, CH_4, and N_2O, as well as other pollutants like NO_x, SO_x, CO, non-methane volatile organic compounds (NMVOCs) and particulate matter (PM), which contribute to global warming, acidification, and photochemical ozone formation. Anthropogenic GHG emissions and air pollution are global problems and their cumulative impacts threaten ecosystems and human health (Penman et al. 2000; Huijbregts et al. 2016).

To contribute to the holistic assessment of potential environmental impacts of deep-sea mining, we present a methodology to systematically quantify the fuel consumption and emissions that could be associated with a potential typical Mn nodule mining operation in the Clarion-Clipperton Zone (CCZ). Fuel demand forms a significant component of the flexible costs of mining operations and consequently affects the feasibility of such undertakings. Moreover, current and future emission regulations could affect deep-sea mining and the transportation of minerals from the mine site to shore and should, therefore, be considered early in the planning process. Lastly, the quantification of fuel and electricity consumption and the corresponding release of emissions can serve as a starting point for the comparison between deep-sea mining and equivalent terrestrial mining processes.

As deep-sea mining operations have not yet started, there is currently no reliable information available on the energy consumption of commercial-scale Mn nodule mining projects. Moreover, technology developers usually keep energy consumption data from experimental tests confidential. Therefore, it is only possible at this point to use publicly accessible energy demand estimates published as part of economic feasibility studies or life-cycle assessments. Because of this, we base our analysis on two economic assessments published by Ramboll IMS and HWWI (2016) and Agarwal et al. (2012), as well as a life-cycle assessment by McLellan (2015). We complement the quantification of the fuel consumption and emissions of the mining operation with our own calculation of the fuel demand associated with the transportation of the Mn nodules to three possible destinations. Following this, we evaluate the results with respect to the three environmental impact categories ‘global warming potential’, ‘acidification potential’ and ‘photochemical ozone formation’. Lastly, we discuss the issue of GHG emissions and air pollution in relation to deep-sea mining in a wider policy context and highlight knowledge gaps that should be addressed prior to the commercialization of the activity. We refrain from including the transportation and metallurgical processing of the Mn nodules on land for reasons related to the limited data availability and accessibility at the current state of development (Das and Anand 2017).

2 Emissions form combustion of HFO in ship engines

The combustion of HFO causes emissions of various GHGs and air pollutants. The quantity of emissions released during the operation of an engine can be influenced by various factors including fuel type, engine type, or installed abatement technology (Penman et al. 2000). During combustion, the C stored within the fuel is almost completely emitted as CO_2. The CO_2 emissions are, thus, directly linked to the C content of the fuel and, therefore, solely influenced by fuel type (Penman et al. 2000; IMO 2014). Similarly, the emissions of SO_x are directly linked to the S content of the fuel, which in HFO typically is between 2 and 3 % but can also reach up to 5%. The incomplete combustion of hydrocarbons causes the release of CH_4, CO, NMVOCs and PM. CO emissions indirectly influence the atmospheric concentration of CH_4 in the atmosphere by reacting with hydroxyl radicals, which would otherwise serve as a sink for CH_4. CO, CH_4, and NMVOC emissions are influenced by fuel type and engine type. NO_x emissions usually comprise NO and NO_2 and are influenced by fuel type and engine type (Penman et al. 2000; IMO 2014).

The release of GHGs and other air pollutants is a function of activity and calculated as the product of the fuel consumption and a pollutant, fuel-type, and engine type specific emission factor (EF) (Penman et al. 2000; IMO 2014; Trozzi et al. 2016). EFs are representative values that link a certain activity to the amount of emissions this particular activity causes per reference unit. They do not, however, provide information on the impact of the respective pollutant. For instance, the EFs can be used to quantify the CO_2, CH_4, and N_2O emissions caused by combusting a certain amount of HFO but they cannot account for the fact that CH_4 and N_2O are considerably more potent GHGs than CO_2. This needs to be considered in a second calculation step using so-called characterization factors (CF) (see section 5.2 of this chapter).

Table 1: *Emission factors for main (EF ME) and auxiliary (EF aux) engines recommended in the Third IMO Greenhouse Gas Study (IMO 2014)*

Type of emission	EF ME [t CO_2/t HFO]	EF AUX [t CO_2/t HFO]	Reference
CO_2 (default)	3.114	3.114	MEPC 63/23, Annex 8
CO_2 (incl. upstream emissions from HFO production and transport)	3.5	3.5	(Kranke et al. 2011; (CEFIC and ECTA 2011)
CH_4	0.00006	0.00004	(Cooper and Gustafsson 2004)
N_2O	0.00016	0.00016	(EPA 2014)
CO	0.0026	0.0024	(Sarvi et al. 2008)
NO_x	0.079	0.049	(IMO 2014)
SO_x (HFO sulfur content 2.7%)	0.053	0.053	(IMO 2014)
PM	0.00728	0.00634	(EPA 2014)
NMVOC	0.00308	0.00176	(ENTEC UK Limited 2002)

Table 1 shows the EFs recommended for slow-speed (main) engines and medium-speed (auxiliary) engines compiled by the International Maritime Organization (IMO) as part of their Third Greenhouse Gas Study (IMO 2014). The values used in the IMO's study were either directly published in official IMO documents, for example in resolutions of the IMO's Marine Environmental Protection Committee (MEPC), or reviewed, discussed, and unanimously agreed upon by the consortium members authoring the IMO's study (for more information see IMO 2014, Annex 6, p. 247).

3 Methodology

There are different methods available for the calculation of emissions from the international shipping fleet (some top-down and others bottom-up), which are selected based on the purpose of the assessment (i.e., the required resolution), the availability of data and the pollutant under consideration (Penman et al. 2000; Trozzi et al. 2016). The Tier 1 method is a top-down approach and usually utilized in cases where a high resolution is not required, or data availability is limited. It is usually based on fuel sales statistics and only differentiates between fuel types. The Tier 2 approach is more specific as it additionally distinguishes between engine types and uses country specific EFs wherever possible (Penman et al. 2000; Trozzi et al. 2016). The Tier 3 approach is a bottom-up method that estimates emissions based on individual ship data. It considers not only fuel and engine types but also operational modes such as cruising, maneuvering, at anchorage (sailing at 1-3 knots) or at berth (sailing at <1 knot) (IMO 2014).

For the calculation of GHG emissions and air pollution resulting from deep-sea mining, we combine Tier 1 and Tier 3 approaches, as the focus is on specific vessels only. For the quantification of CO_2, N_2O, and SO_x we follow the Tier 1 approach as these emissions are solely influenced by fuel type. For the calculation of CH_4, CO, PM, NO_x, and NMVOC emissions we use the Tier 3 approach to differentiate between engine type and operational modes (only for the transport vessels, as the mining vessel remains mostly stationary). Concerning engine types, we assume that the energy required for the propulsion of the mining and transport vessels is generated by the ship's main engine (slow-speed diesel engine), whereas electricity for the operation of the mining equipment is generated by its auxiliary engines (medium-speed diesel engines). For the quantification of the fuel consumption of the mining and transport vessels we follow the steps outlined in this section using the parameters presented in Tables 2 and 3. The set-up and scope of a hypothetical commercial nodule mining operation is described in section 4. For the purpose of this assessment, we did not account for the speed of the mining vessel in addition to the energy demand allocated to propulsion. For comparison, a bulk carrier vessel belonging to the SUPRAMAX size class (~58,000 DWT) moving at the speed of the mining collector (0.5 m/s or 0.97 knots) would consume about 0.13 t/d.

The extraction and shipboard processing component (i.e., mining vessel)

$$C_{mining,annual} = \left[\left(EC_{ME,\ annual} \times SFOC_{ME}\right) + \left(EC_{AE,\ annual} \times SFOC_{AE}\right)\right]$$

Where:

$C_{mining,\ annual}$ = annual fuel consumption of mining equipment and vessel [t]

$SFOC_{ME}$ = specific fuel oil consumption main engine [t/kWh]

$SFOC_{AE}$ = specific fuel oil consumption auxiliary engine [t/kWh]

$EC_{ME,\ annual}$= annual energy demand of the mining vessel’s main engine [kWh]

$EC_{AE,\ annual}$ = annual energy demand of the mining vessel’s auxiliary engine [kWh]

2) The emissions of the mining vessel and equipment are calculated as follows:

$$E_{p,mining} = C_{mining,annual} \times EF_{p}$$

Where:

$E_{p,\ mining}$ = emissions of pollutant p from mining equipment and vessel

$C_{mining,\ annual}$ = annual fuel consumption of mining equipment and vessel [t]

EF_{p} = emission factor for pollutant p

In cases where the EF differs for main and auxiliary engines, the emissions have to be calculated separately with the appropriate EFs and summed afterwards.

The transport component

The fuel consumption needed for the transport of the recovered marine minerals requires the determination of several parameters such as engine power and engine load factor, ballast load factor, travel distance, speed, and the specific fuel consumption (SFOC) of the main and auxiliary engines. Furthermore, it is important to determine the time spent in cruising mode, at anchorage, and at berth, as this affects the operation of the engines. Lastly, it is necessary to determine how many transport cycles are needed per year based on the annual production of the mine and the storage and transport capacity of the mining and transport vessels. Each transport cycle consists of a single distance traveled in laden condition, one in ballast condition, as well as time for transshipment at sea and in port at either end of the trip. While the main engine is operated only during sailing, the auxiliary engines are running permanently, i.e., during sea passage and (un)loading operations.

Calculation of the required main engine power at desired speed:

$$\mathrm{M}_{ME,d} = \mathrm{l}_{\mathrm{ME}} \times \mathrm{M}_{\mathrm{ME}} \times (d/\mathrm{D})^2$$

Where:

$M_{ME,\,d}$ = main engine output at desired speed [kW]

M_{ME} = maximum load of main engine [kW]

l_{ME} = load factor of main engine, in this case 0.85

D = design speed (maximum speed according to vessel manufacturer) [NM/h]

d = desired speed [NM/h]

Calculation of daily fuel consumption of the main engine at desired speed:

$$C_{ME,\ daily,\ d} = M_{ME,d} \times SFOC_{ME} \times 24$$

Where:

$C_{ME,daily,d}$ = daily fuel consumption at desired speed d [t]

$M_{ME,d}$= main engine load at desired speed [kW]

d = design speed [NM/h]

$SFOC_{ME}$ = specific fuel oil consumption [g/kWh]

Calculation of the annual fuel consumption of the main engine for N round trips (round trips consist of a single voyage in laden condition and one voyage in ballast condition, as well as time at anchorage and at berth).

$$C_{ME,annual} = \left[\left(C_{ME,\ daily,\ d} \times t_d\right) + \left(b \times C_{ME,\ daily,\ d} \times t_d\right)\right] \times N$$

Where:

$C_{ME,annual}$ = total annual fuel consumption of the transport vessels‘ main engines at desired speed d [t]

t_d = travel time for one-way transport between mining operation and port [d]

b = ballast load factor, in this case 0.85 (reduction factor for operation in ballast condition, i.e., reduced resistance due to smaller ships displacement)

N = number of round trips per year

Calculation of the total fuel consumption of the transport vessels' auxiliary engines:

The calculation of the annual fuel consumption of the auxiliary engines largely follows that of the main engine. It is affected by the time spent in each operational mode. For the auxiliary engine, it is not important to differentiate whether the ship travels in laden or ballast condition.

$$C_{AE,annual} = \left(\left(M_{AE,s} \times SFOC_{AE} \times t_s \right) + \left(M_{AE,b} \times SFOC_{AE} \times t_b \right) + \left(M_{AE,a} \times SFOC_{AE} \times t_a \right) \right) \times N$$

Where:

$C_{AE,annual}$ = total annual fuel consumption of auxiliary engines [t]

$M_{AE,\,s}$ = engine load of the auxiliary engine (cruising) [kW]

$M_{AE,\,a}$ = engine load of the auxiliary engine (at berth) [kW]

$M_{AE,\,b}$ = engine load of the auxiliary engine (at anchorage) [kW]

t_s = time spent cruising [h]

t_b = time spent at berth [h]

t_a= time spent at anchorage [h]

N = number of round trips per year

Calculation of the total fuel consumption from transportation of mineral ores:

$$C_{total,annual} = C_{ME,annual} + C_{AE,annual}$$

Where:

$C_{ME,annual}$ = total annual fuel consumption of main engines [t]

$C_{AE,annual}$ = total annual fuel consumption of auxiliary engines [t]

$C_{total,annual}$ = total annual fuel consumption of main and auxiliary engines [t]

Calculation of emissions from transportation of mineral ores:

$$E_{p,transport} = C_{transport,\ annual} \times EF_p$$

Where:

$E_{p,transport}$= Emissions of pollutant p from mining equipment and vessel

$C_{transport,\ annual}$ = Annual fuel consumption of mining equipment and vessel [t]

EF_p = Emission factor for pollutant p

4 Case study: Mn nodule mining in the CCZ

In the absence of publicly accessible data on existing commercial-scale technology, we base our assessment on energy demand estimates presented in the literature by Agarwal et al. (2012), McLellan (2015), and Ramboll IMS and HWWI (2016) (Figure 7). While the three mining systems are generally similar, they differ with respect to the number of collector vehicles or mining vessels in operation, as well as the annual production and operational time. For instance, Agarwal et al. (2012) propose a modular mining system capable of mining 1.5 million t per year (dry weight), consisting of 9 hybrid-type collector vehicles, which are attached to three mining vessels (three collectors per vessel). The collector vehicles are modeled based on the South Korean MineRo experimental collector (Hong et al. 2010) although a hydraulic type is chosen instead of the original hybrid type. The collector vehicles are connected via flexible riser pipes to a joint black box, which acts as a buffer to ensure an even flow of Mn nodule material. From the buffer, the Mn nodules are pumped upward to the mining vessel through a shared rigid riser pipe. Onboard the mining vessel, which is equipped with a dynamic positioning system, the Mn nodules are washed, dewatered, partially dried and stored until they are picked up by bulk carrier vessels. One mining system consisting of a mining vessel and three collector vehicles requires 16.2 MW (11.5 MW equipment, 4.7 MW mining vessel), amounting to approximately 50 MW for the entire mining operation (0.5 million t of Mn nodules (dry weight) retrieved from 5,000 m water depth).

McLellan (2015) uses a similar mining concept, which, however, relies on only one mining vessel and one collector vehicle to produce 1.5 million t of Mn nodules per year (dry weight). The energy consumption of the mining equipment is a direct proportional scale-up of the Indian Integrated Mining System described by Atmanand (2011). The hydraulic system was tested in the Central Indian Ocean using artificially produced and distributed nodules at a water depth of 500 m. The energy consumption to mine 1.5 million t of Mn nodules (dry weight) at a water depth of 5,000 m amounts to about 30 MW (23 MW equipment, 7 MW mining vessel).

The mine set-up envisioned by Ramboll IMS and HWWI (2016) builds on recent findings of the European Union's Blue Mining and Blue Nodules projects and centers around a hydraulic mining system consisting of two collector vehicles, which are connected to a buffer by means of flexible riser pipes. From the buffer, which ensures a continuous and even flow, the nodule material from both collector vehicles is pumped upward to the mining vessel through a rigid riser pipe. Onboard the mining vessel, which is equipped with active propulsion and dynamic positioning, as well as onboard handling and transport systems and storage facilities, the nodules are washed and stored until they are picked up by two to three bulk carrier vessels and transported to shore. The energy demand for a nodule operation with an annual production of 3 million t of Mn nodules (dry weight) is estimated to be 16.37 MW (14.12 MW equipment, 2.25 MW mining vessel) based on the company's long-time experience in the offshore engineering sector. To make all of the energy demand estimates comparable, we adjusted them to fit a Mn nodule mining operation at 5,000 m water depth, which is operational over 300 days per year with an annual production of 3 million t (dry weight) (UNOET 1987).

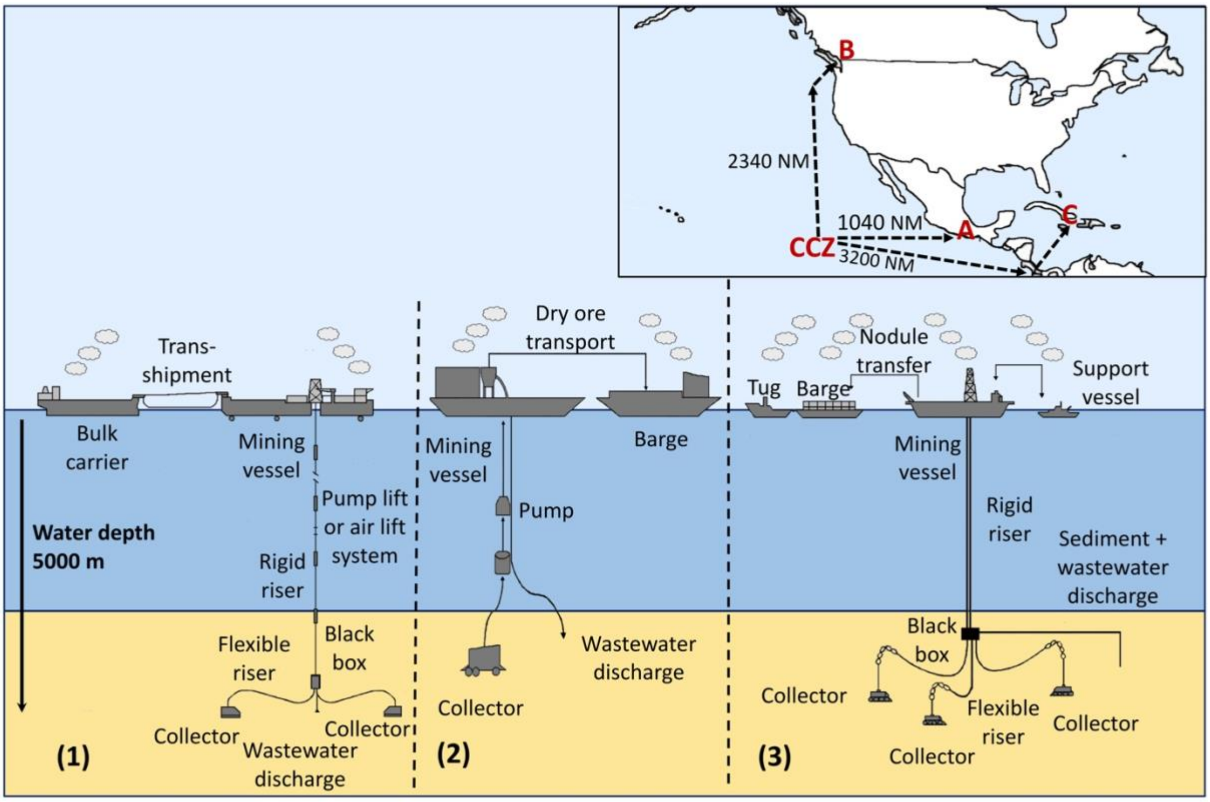

Figure 7: Schematic overview of the mining concepts outlined by and modified after (1) Ramboll (2016), (2) McLellan (2015) and (3) Agarwal et al (2012) as well as a schematic overview of the transport locations (A) Port of Lázaro Cárdenas, Mexico, (B) Port of Vancouver, Canada, and (C) Port of Santiago de Cuba, Cuba (Reprinted from Heinrich et al. 2020).

We calculated the fuel consumption and the corresponding emissions for three transport routes to three different possible processing locations on land (Figure 7). The first destination port is Lázaro Cárdenas in Mexico (1,040 NM), which is the port located closest to the CCZ. Due to its relative proximity to the CCZ, this presents the most economical option. The second potential transport destination is the Port of Vancouver in Canada (2,340 NM), which is a suitable processing location from a sustainability-focus due to the larger share of renewable energy in the Canadian energy mix (IEA 2016; 2017). The third transport destination is the Port of Santiago de Cuba in Cuba (3,200 NM). Cuba may be a suitable processing location due to its relative proximity to the CCZ and the country's experience with the processing of terrestrial nickel laterites, which are considered to be similar to Mn nodules with respect to their metallurgical processing (Das and Anand 2017). For the purpose of this study, we assume that bulk carriers carry out the transport of fuel, personnel, and Mn nodules. Tables 2 and 3 show the assumptions of the input values for the calculation of the fuel consumption associated with the mining and transport vessel and the mining equipment.

Table 2: *Energy demand estimates for a hypothetical mining operation with an annual production of 3 million t of nodules (dry weight) based on assessments by Ramboll IMS and HWWI, (2016), McLellan (2015) and Agarwal et al. (2012).*

Energy demand estimates (per 3 million t/yr dry weight)		
Ramboll-HWWI (2016) Mining vessel: 2.25 MW Mining equipment: 14.1 MW	McLellan (2015) Mining vessel: 14 MW Mining equipment: 46 MW	Agarwal et al. (2012) Mining vessel: 78 MW Mining equipment: 191.7 MW
Annual production: 3 million t (dry weight)		
Annual operational time: 300 d		
Water depths: 5,000 m		
SFOC main engine: 170 g HFO/kWh (based on the General Arrangement Plan of a bulk carrier vessel of similar size), 195 g HFO/kWh(International Maritime Organization (IMO) 2014)used as default value, if not indicated otherwise)		
SFOC auxiliary engine: 227 g/kWh		

Table 3: *Overview of input values for the transport vessels*

Engine load
Main engine
Maximum engine load (100%): 8,400 kW (based on the General Arrangement Plan of a bulk carrier vessel of similar size)
Engine Load factor: 0.85 (based on the General Arrangement Plan of a bulk carrier vessel of similar size)
Engine load at design speed (14.5 knots): 7,410 kW (based on the General Arrangement Plan of a bulk carrier vessel of similar size)
Engine load at desired speed (12 knots): 4,890.2 kW
Ballast load factor: 0.85
Auxiliary engine
Engine load: at sea 260 kW, at berth 370 kW, at anchorage 260 kW (average values provided by IMO 2014)
Specific fuel oil consumption
Main engine
SFOC: 170 g HFO /kWh (based on the General Arrangement Plan of a bulk carrier vessel of similar size), 195 g/kWh (IMO 2014) used as default value, if not indicated otherwise
Auxiliary engine
227 g HFO /kWh (IMO 2014)
Time considerations
Main engine
Time required for single distance at 12 knots: 3.61 d (Mexico), 8.15 d (Canada), 11.11 d (Cuba)
Time required for single distance at 14.5 knots: 2.99 d (Mexico), 6.74 d (Canada), 9.19 d (Cuba)
Aux engine
Time required for single distance at 12 knots: 3.61 d (Mexico), 8.15 d (Canada), 11.11 d (Cuba)
Time required for single distance at 14.5 knots: 2.99 d (Mexico), 6.74 d (Canada), 9.19 d (Cuba)
Time of loading/unloading (transshipment): at berth 2 days, at anchorage 1.5 days (loading rate: 2000 t/h + buffer)
Number of round trips per year: 60 (assuming an annual production of 3 million t of Mn nodules (dry weight) and a bulk carrier transport capacity of 50,000 t of Mn nodules (dry weight).

5 Results

5.1 Quantification of HFO consumption and associated emissions to air

Figs. 8–16 depict the results of the calculation of the annual fuel consumption and resulting emissions of the hypothetical mining operation in the CCZ and the three transport scenarios. Figures 8 and 9 show the HFO consumption of deep-sea mining operations based on the three different energy demand estimates by Agarwal et al. (2012), McLellan (2015), and Ramboll IMS and HWWI (2016) and the transport to the three different processing locations in Mexico, Canada, and Cuba, respectively. Figure 10 provides the amount of CO_2 emissions associated with the entire mining operation (mining and transport). Figures 11 and 12 focus on CO_2 emissions whereas figures 13 and 14 concentrate on the remaining GHG emissions, CH_4 and N_2O. Lastly, Figures 15 and 16 show emissions of the remaining pollutants to air, namely CO, PM, NMVOCs, NO_x, and SO_x. Of the above-mentioned figures, only figure 12 consdiders 'well-to-wheel' emissions, of the mining operation (mining vessel and equipment), which incorporate not only the emissions caused by the combustion of the HFO on site but also the emissions caused during the production of the HFO and its transport to the vessels. The fuel consumption is multiplied with an EF specifically for the calculation of well-to-wheel emissions of bulk carrier vessels.

The demand estimates for the mining operation (mining vessel and equipment) translate to approximately 26,100t HFO, 95,000t HFO, and 423,240 t HFO for the Ramboll IMS and HWWI (2016), the McLellan (2015), and the Agarwal et al. (2012) set-ups, respectively. The transportation of no- dules to Mexico, Canada, and Cuba by means of bulk carrier vessels of the SUPRAMAX size class (50,000 DWT) requires 10,157t HFO, 22,447t HFO, and 30,465t HFO, respectively. Common to all three mining scenarios is the assumption that energy consumption of the mining equipment is higher than that of the mining vessel and of the transport component. The latter, however, depends on the distance between the mine site and the port.

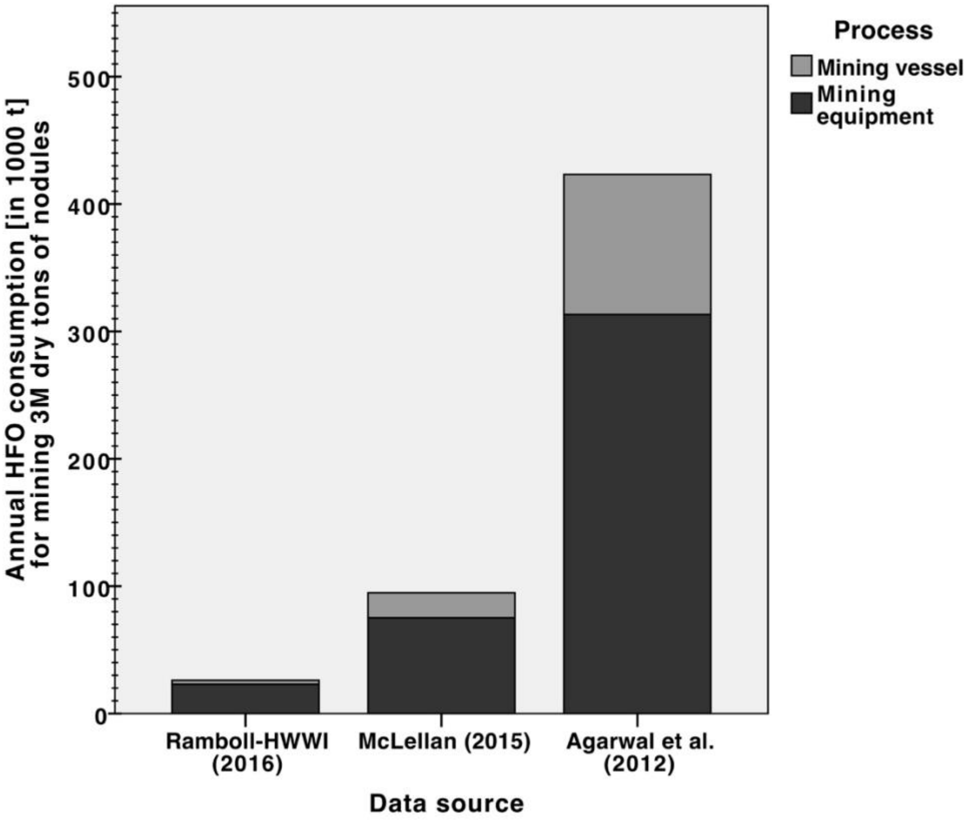

Figure 8: Annual HFO consumption of a 3 million t Mn nodule mining operation (dry weight) subdivided into mining vessel and mining equipment based on energy demand estimates from three different sources (reprinted from Heinrich et al. 2020).

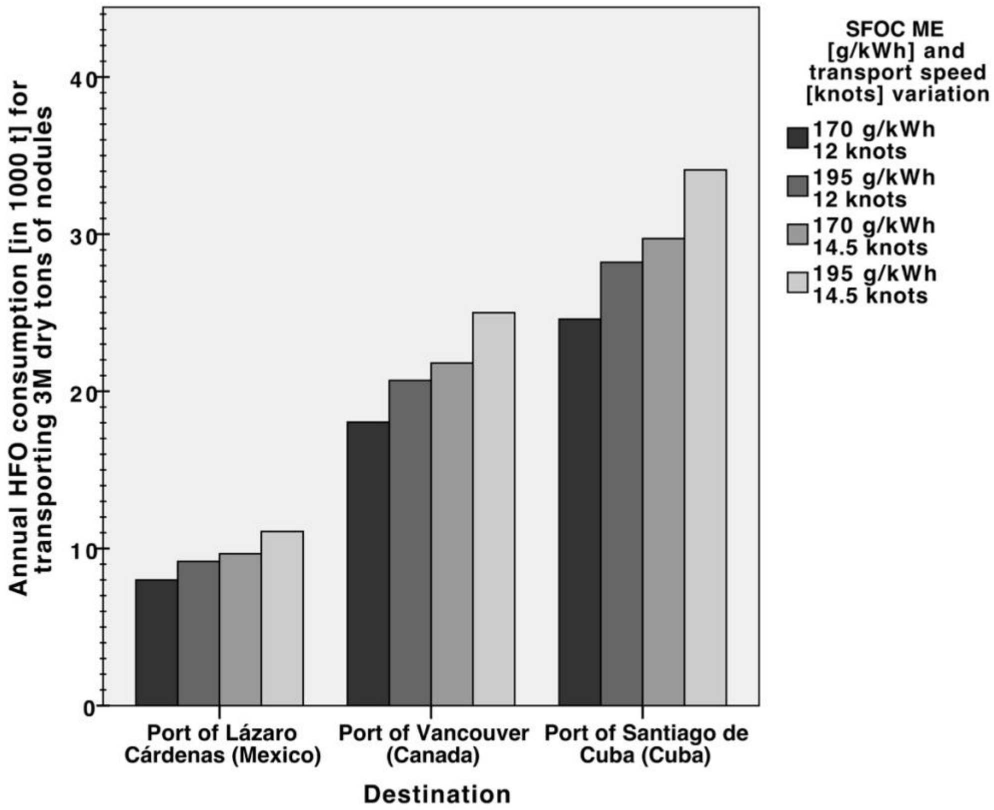

Figure 9*: Annual HFO consumption for transport of 3 million t of Mn nodules (dry weight) to different destinations (reprinted from Heinrich et al. 2020).*

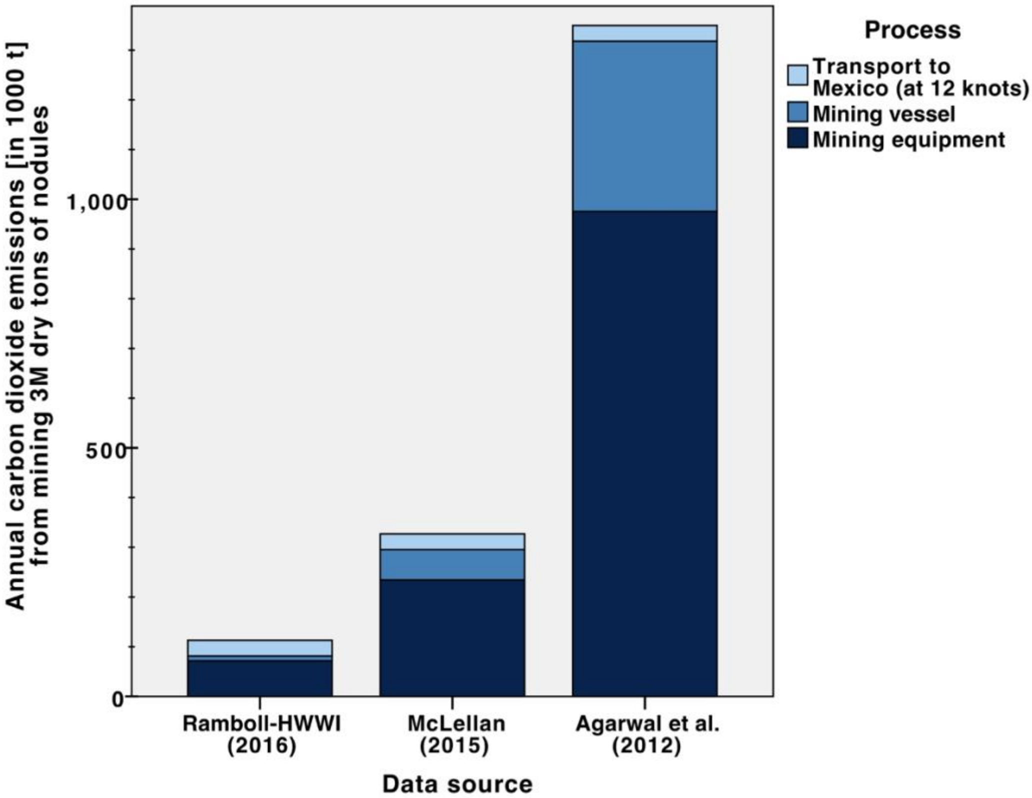

Figure 10: *Annual CO_2 emissions a 3 million t Mn nodule mining operation (dry weight) subdivided into mining vessel, mining equipment and transportation (from the CCZ to Mexico) based on energy demand estimates from three different sources (reprinted from Heinrich et al. 2020).*

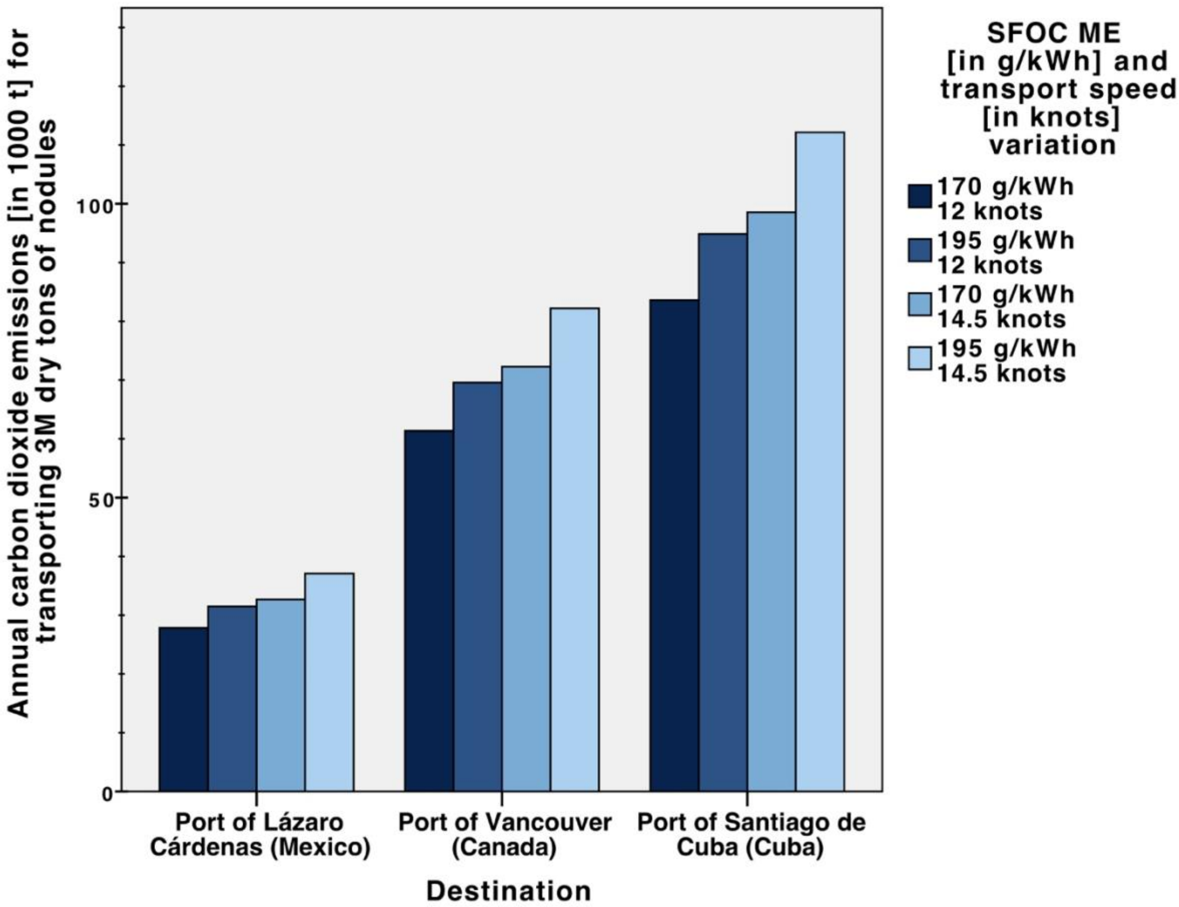

Figure 11: *Annual CO_2 emissions for transport of 3 million t of Mn nodules from the CCZ to different locations with variations of the specific fuel oil consumption of the main engine (SFOC ME) and the transport speed (reprinted from Heinrich et al. 2020).*

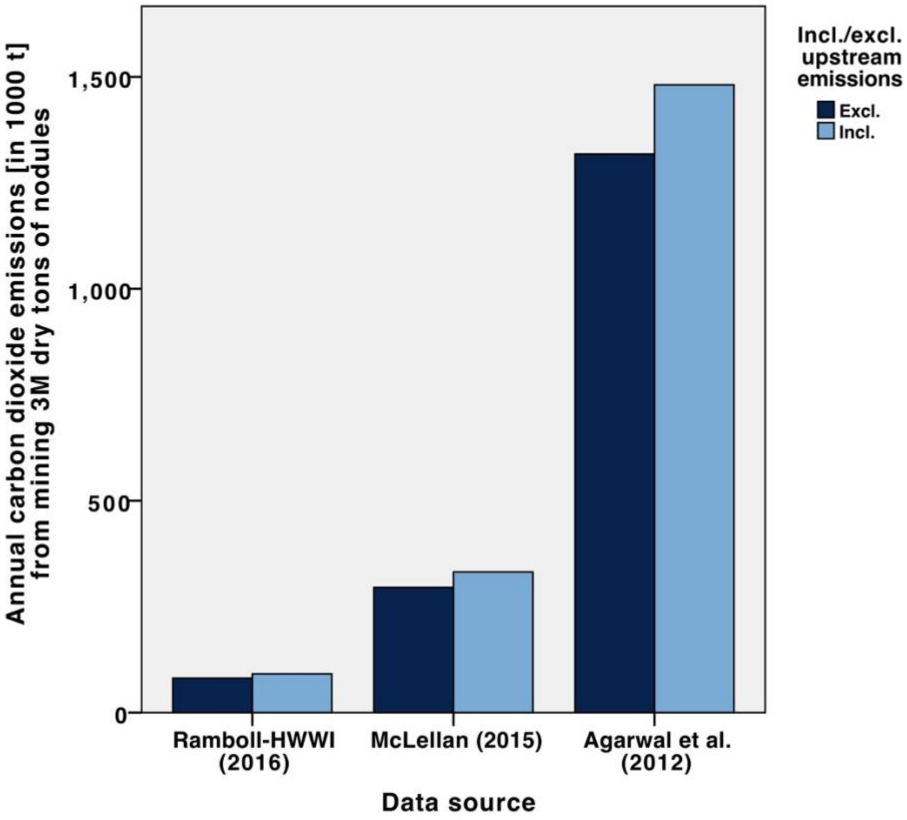

Figure 12: *Annual CO_2 emissions for a 3 million t Mn nodule mining operation (dry weight) arising from the combustion of the HFO (excl. combustion upstream emissions) and well-to-wheel (incl. combustion and upstream emissions) based on energy demand estimates from different sources (reprinted from Heinrich et al. 2020).*

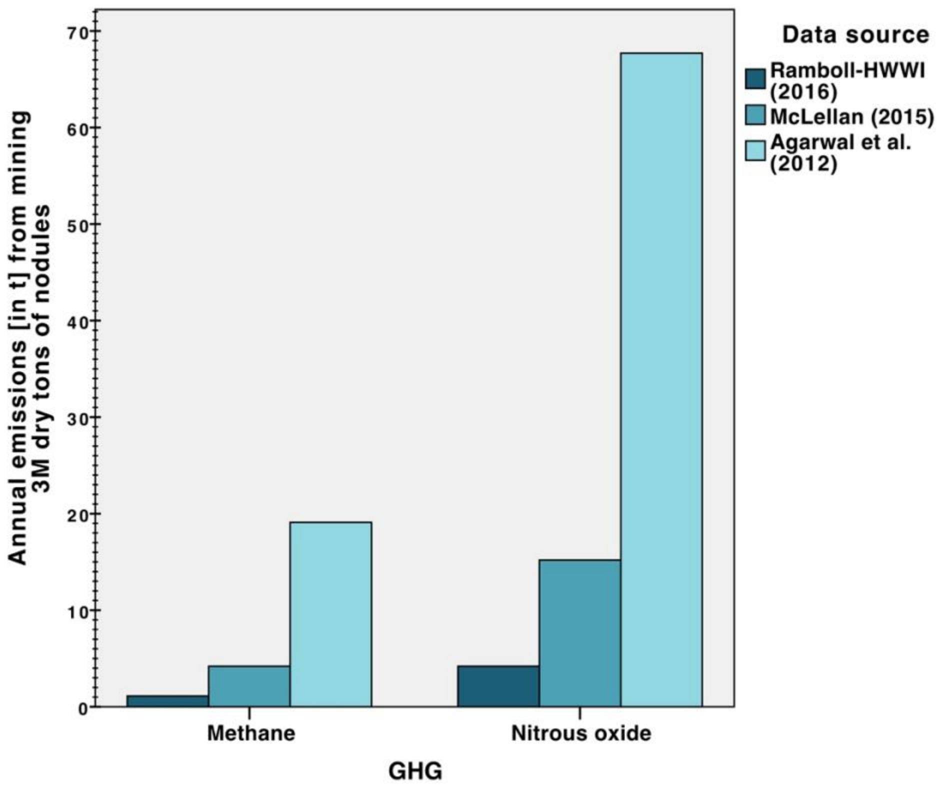

Figure 13: Annual CH_4 and N_2O emissions for a 3 million t Mn nodule mining operation (dry weight) based on energy demand estimates from different sources (reprinted from Heinrich et al. 2020).

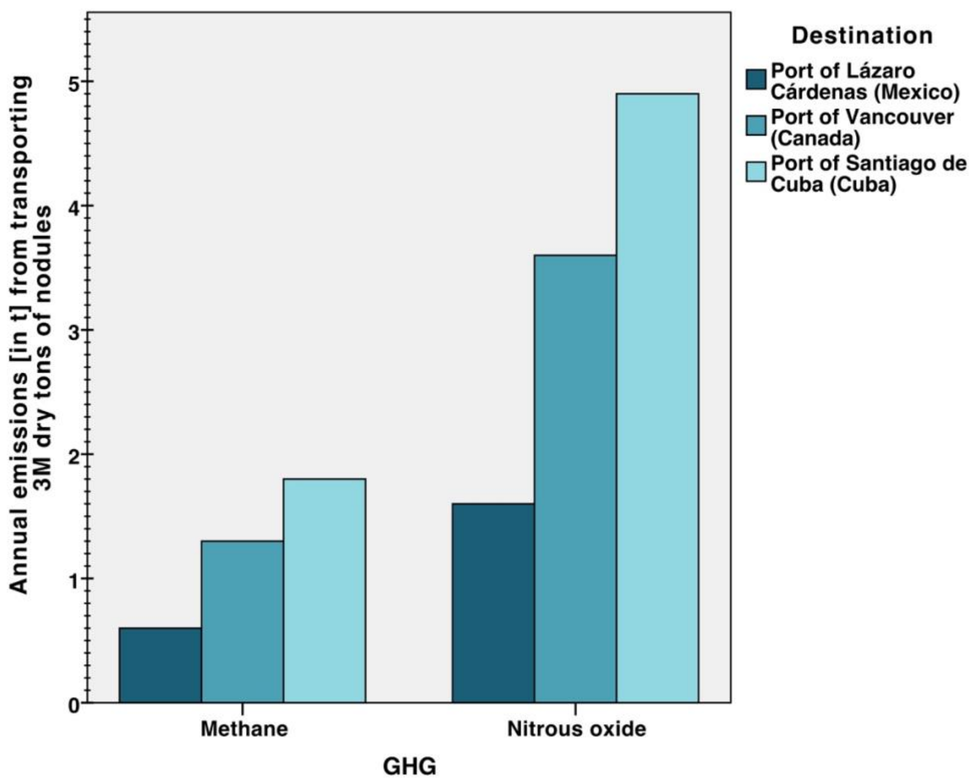

Figure 14: Annual CH_4 and N_2O emissions for transporting 3 million t of Mn nodules (dry weight) from the CCZ to different destinations (reprinted from Heinrich et al. 2020).

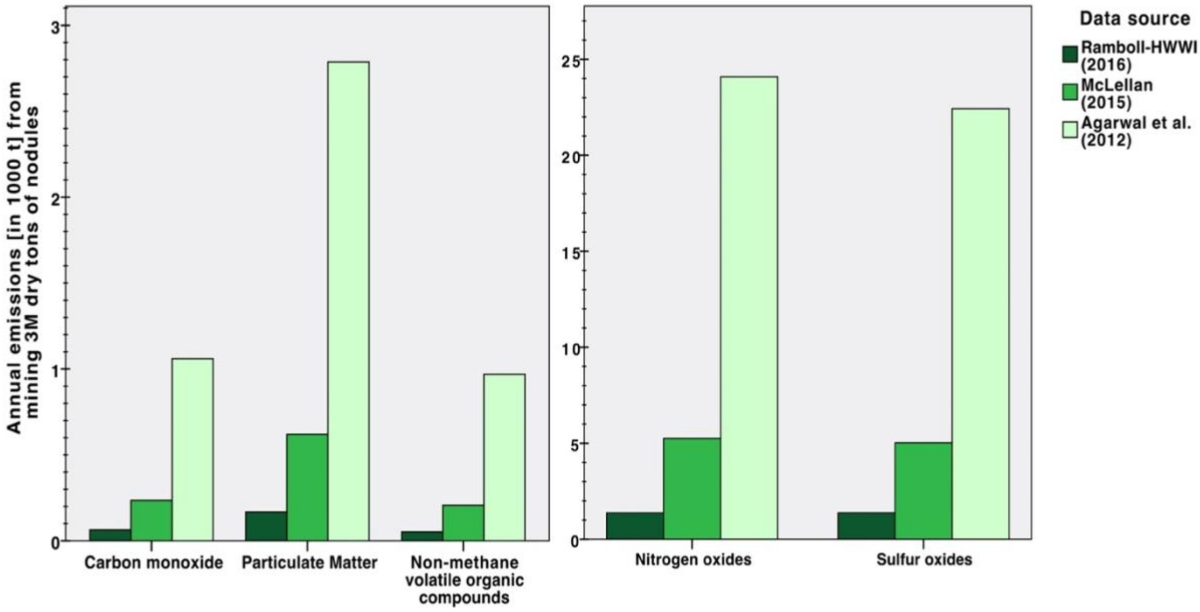

Figure 15: *CO, PM, NMVOC, NO_x and SO_x emissions for a 3 million t Mn nodule mining operation (dry weight) based on energy demand estimates from three different sources (reprinted from Heinrich et al. 2020).*

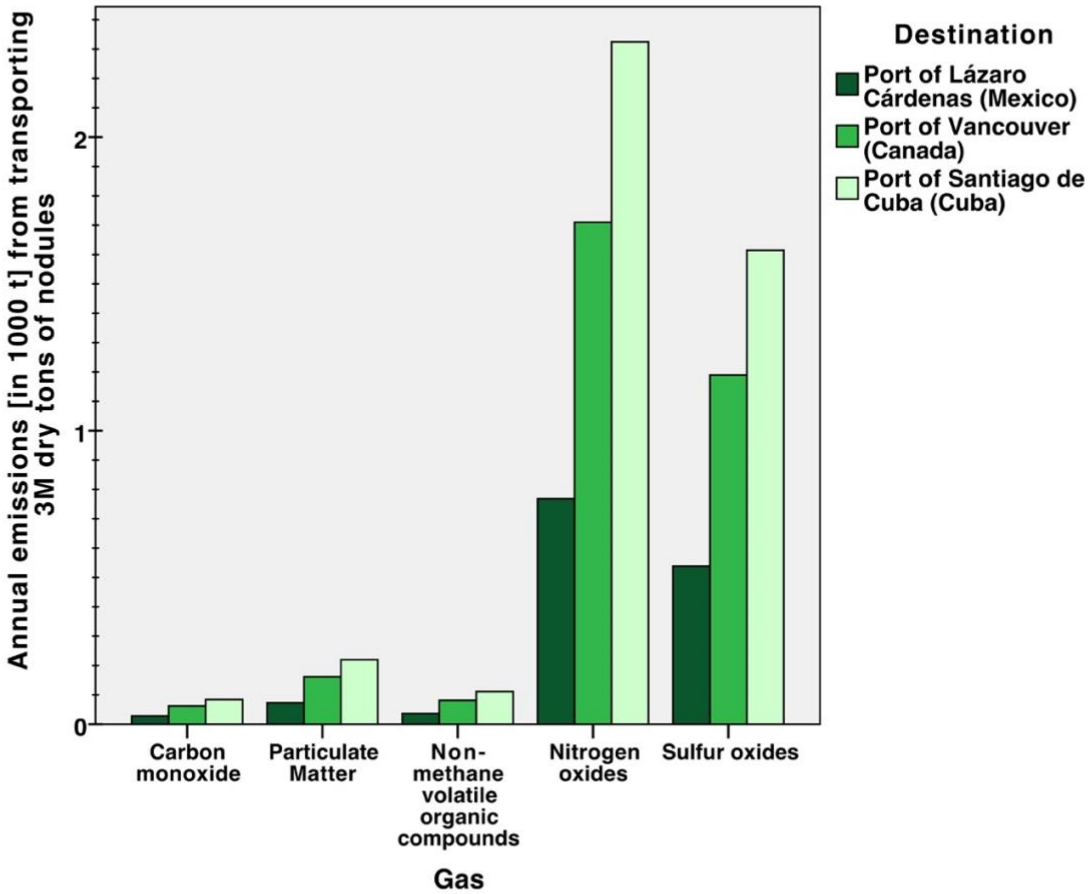

***Figure 16**: CO, PM, NMVOC, NO_x and SO_x emissions for transporting 3 million t of Mn nodules (dry weight) from the CCZ to different destinations (reprinted from Heinrich et al. 2020).*

5.2 Impact assessment

Life-cycle impact assessment (LCIA) is a method to evaluate and compare different environmental impacts such as GHG emissions and air pollution with respect to their influence on ecosystem well-being and human health. The impacts are typically grouped into several impact categories suitable for the pollutants or processes under consideration (Rebitzer et al. 2004). To make the pollutants contributing to the individual impact categories comparable, they are normalized through multiplication with pollutant specific characterization factors (CFs). In contrast to EFs (see section 2 in this chapter), CFs account for the magnitude of the impact of individual pollutants (Huijbregts et al. 2016). LCIAs can evaluate environmental impacts occurring along a production chain at different stages of the impact pathway: at mid-point level (e.g., 'global warming,' 'acidification potential,' and 'photochemical ozone formation') or at end-point level (e.g., 'damage to human health,' 'damage to ecosystems,' and 'damage to resource availability'). For the purpose of this study, we focus on mid-point level impacts. Assessments at mid-point level show lower uncertainty whereas those at end-point level provide more information about the relevance of individual impacts (Huijbregts et al. 2016). Due to our focus on air pollution resulting from the combustion of HFO and the limited number of pollutants, we focus on the mid-point level categories 'global warming potential', 'terrestrial acidification,' and 'photochemical ozone formation.'

For the calculation of the 'global warming potential' we used CFs provided as part of the ReCiPe method (Huijbregts et al. 2016). We set the resulting index, the ‚total global warming potential' (GWP) to the defined period of 100 years. Table 4 shows the GWP100, expressed in t of CO_2 equivalent (t CO_2-eq.), for the hypothetical mining operation (mining vessel and equipment) outlined in section 4 in this chapter based on the energy demand estimates provided by Ramboll IMS and HWWI (2016), McLellan (2015), and Agarwal et al. (2012) using default EFs. Emissions of SO_x and NO_x cause acidic deposition (e.g., 'acid rain'), which leads to soil acidification and is harmful to the majority of plant species. Table 5 shows the acidification potential of the hypothetical deep-sea mining operation caused by SO_x and NO_x emissions expressed as t of SO_x equivalent (t SO_x-eq.). NO_x and NMVOC emissions contribute to photochemical ozone formation and are expressed as t of NO_x equivalent (NO_x-eq.) in table 6. Tropospheric ozone can cause respiratory stress, inflammation of airways and lung damage. Besides human health, ozone can also negatively affect ecosystems, specifically plant growth, and seed production. It can also decrease their overall resilience to other stressors (Ashmore 2005; Gerosa et al. 2015).

Table 4: *Total global warming potential (GWP 100) for mining 3 million t of Mn nodules (dry weight) ($SFOC_{ME}$: 195 g HFO/kWh) (rounded values).*

Pollutant	Emissions [in t]			Conversion factor (Huijbregts et al. 2016)	GWP100 [in t CO_2-eq.]		
	Ramboll-HWWI (2016)	McLellan (2015)	Agarwal et al. (2012)		Ramboll-HWWI (2016)	McLellan (2015)	Agarwal et al. (2012)
CO_2	81,294	295,327	474,469	1	81,294	295,327	474,469
CH_4	1	4	7	34	38	143	235
N_2O	4	15	24	298	1,252	4,530	7,271
Total GWP100 [t CO_2-eq.]					**82,584**	**300,000**	**481,975**

Table 5*: Total acidification potential for mining 3 million t of Mn nodules (dry weight) ($SFOC_{ME}$: 195 g HFO/kWh) (rounded values).*

Pollutant	Emissions [t GHG]			Conversion factor (Huijbregts et al. 2016)	Acidification potential [t SO2-eq.]		
	Ramboll-HWWI (2016)	McLellan (2015)	Agarwal et al. (2012)		Ramboll-HWWI (2016)	McLellan (2015)	Agarwal et al. (2012)
SO_2	1,384	5,026	8,075	1	1,384	5,026	8,075
NO_x	1,380	5,252	8,671	0.36	497	1891	3,122
Acidification potential [in t SO_2-eq.]					**1,881**	**6,917**	**11,197**

Table 6: *Total photochemical ozone formation potential for mining 3 million t of Mn nodules (dry weight) ($SFOC_{ME}$: 195 g HFO/kWh) (rounded values)*

Pollutant	Emissions [t GHG]			Conversion factor (Huijbregts et al. 2016)	Photochemical Ozone Formation [t NO_x-eq.]		
	Ramboll-HWWI (2016)	McLellan (2015)	Agarwal et al. (2012)		Ramboll-HWWI (2016)	McLellan (2015)	Agarwal et al. (2012)
NO_x	1,380	5,252	8,671	1	1,380	5,252	8,671
NM VOC	52	207	349	0.18	9	37	63
Photochemical ozone formation [in t NO_x-eq.]					**1,389**	**5,289**	**8,734**

6 Discussion of results

The results deliver a first indication of the potential level of emissions expected to arise annually as a direct consequence of Mn nodule mining. However, it is important to note in this regard that the values are based on three sets of energy demand estimates derived from offshore engineering experience and scale-ups of experimental tests rather than data from actual commercial-scale operations.

The energy demand estimates provided by Ramboll IMS and HWWI (2016), McLellan (2015), and Agarwal et al. (2012) are vastly different. Based on these estimates, the mining concept envisioned by Ramboll IMS and HWWI (2016), which assumes by far the lowest energy demand would be the most suitable to reduce greenhouse gas and air pollution. Recent estimates in unpublished reports appear to confirm an energy demand of this magnitude for a nodule mining operation with annual production of three million t (dry weight)[3]. While the Ramboll IMS and HWWI (2016) energy demand estimates are based on the company's long-term experience in the field of offshore engineering, McLellan (2015) bases his energy demand estimates on a direct upscaling of the collector vehicle developed and described by (Atmanand 2011; Atmanand and Ramadass 2017). This experimentally tested mine system consisting of a collector vehicle, crusher and a positive displacement pump was tested at 500 m water depth using artificially produced and distributed nodules. To test for sensitivity, McLellan (2015) further compared the results from the scale-up with the energy demand of a single mining tool developed for the Solwara I project, which aims at mining SMS deposits in the EEZ of Papua New Guinea. McLellan (2015) also clearly states that the Mn nodules will be lifted by means of a hydraulic lifting system. However, the energy needed to cut sulfides and hard rock during the sulfide mining process may be considerably higher than the demand for Mn nodule mining. In fact, the energy demand provided by McLellan (2015) appears to be higher than more recent unpublished estimates suggest. Agarwal et al.'s (2012) proposed collector vehicle is inspired by the South Korean MineRo experimental collector, although Agarwal et al. (2012) envision a hydraulic collector instead of the original hybrid-type. They expect the energy demand of both collectors to be of the same order of magnitude. However, the mine set-up consisting of nine collector vehicles and three mining vessels to mine 1.5 million t of Mn nodules (dry weight) per year is very unusual compared to the majority of the pro-posed mining concepts (Blue Mining, 2017; Blue Nodules, 2019; McLellan, 2015; Ramboll IMS and HWWI, 2016). The energy demand (95.5 MW) also appears to be extraordinarily high. For comparison, the most powerful commercially deployed wind turbines have a power rating of 8.8 MW (offshore), trend increasing. This mining concept would probably be associated with very high capital and operational costs, which would severely affect

[3] Kuhn, T. Bundesanstalt für Geowissenschaften und Ressourcen (2019). Personal communication.

the economic feasibility of the mining operation. With respect to the mining vessel, the differences in energy can likely be attributed to the dimensions of the vessels and the number of vessels required per mining system. For example, while the Ramboll IMS and HWWI (2016) claim to require one mining vessel with a length of 270 m and a width of 40 m to produce 3 million t of Mn nodules (dry weight) per year, Agarwal et al. (2012) envision the use of three mining vessels of 170 m length and 40 m width to mine 0.5 million t of Mn nodules (dry weight) per year.

Once deep-sea mining reaches a more advanced planning and development stage, it will be necessary to update and refine these assessments, for example with respect to the choice of main and auxiliary engines, their SFOC and engine output, the mining equipment’s energy demand at a commercial scale, the transport vessels under consideration, their fuel demand, route and speed, and the time spent in different operational modes. Moreover, it will eventually be possible to determine the energy demand required for hoteling, which depends on the number of workers and crew onboard the mining and transport vessels. For example, Ramboll IMS and HWWI (2016) assume that mining vessel will carry 58 workers, which based on their energy demand estimate would cause, inter alia, an additional 6,107 t CO_2, 97 t NO_x and 104 t SO_x for a mining operation with an annual production of 3 million t of Mn nodules (dry weight). The contribution from the hoteling of workers may even be higher, as Van Nijen et al. (2018) assume that 70 people will work onboard the mining vessel. The newly built mining vessel for the Solwara I project (‘Nautilus New Era’) could even provide space for around 199 workers (Sarangdhar 2018). Commercial-scale mining operations may also require the use of Remotely Operated Vehicles (ROVs) and Seafloor Working Units (SWUs), which, based on the Ramboll IMS and HWWI (2016) estimate, would cause the additional annual emission of, inter alia, 5,090 t CO_2, 81 t NO_x, and 87 t SO_x.

Furthermore, for the purpose of this assessment, we did not account for the transport of fuel, crew and supplies to the mining vessel. In the open ocean, it is likely that mining vessels will have to be re-fueled via ship-to-ship bunkering. Furthermore, for the purpose of this assessment, we did not account for the transport of fuel, crew and supplies to the mining vessel. In the open ocean, it is likely that the mining vessel has to receive fuel via ship-to-ship bunkering. Drill ships, which may be comparable to deep-sea mining vessels, typically have a bunkering capacity between 5,000 and 10,000 t (Savvides and Fisk 2015). Seagoing bunkering vessels are capable of bunkering between 1,000 and 10,100 m^3 of HFO or MDO, which translates to about 990 t to 9,900 t HFO, respectively (ISO 8217:2017). Thus, assuming that a commercial-scale mining vessel has a bunker capacity of 9,000 t, a bunkering vessel with a capacity of 9,000 t would have to approach the mine site about 3, 11, or 47 times per year to supply fuel to the mining operations outlined by Ramboll IMS and HWWI (2016), McLellan (2015), and Agarwal et al. (2012), respectively. Ship-to-ship bunkering is challenging and mostly carried out in sheltered areas outside ports to decrease port congestion. Moreover, many ship-to-ship bunkering systems require good weather conditions and calm waters. For the purpose of commercial deep-sea mining, it may, therefore, be necessary to develop strong seagoing ship-to-ship bunkering vessels that can operate under moderate to rough weather conditions without risking oil spills that could cause harm to the environment.

With respect to the transport destinations, Mexico and Canada appear to be the most realistic options, as the transport to Cuba would have to pass through the Panama Canal, which causes a considerable time delay and additional costs for passages. Moreover, Cuba, which imports a significant quantity of oil from the economically and politically unstable Venezuela and is vulnerable to blackouts caused by extreme weather events, may not be capable of providing a stable electricity supply for the processing of nodules. With respect to the other two potential processing locations, there may be a tradeoff between the share of renewable energy in the destination country's energy mix and the longer transport distance to the coast.

7 Regulation of GHG emissions and air pollution

GHG emissions and air pollution resulting from deep-sea mining potentially fall within the general remit of at least three different international regimes that have environmental mandates, namely on climate, on deep-sea mining, and on shipping. While in principle these three regimes function independently from each other, they could intersect concerning governance in a specific area, e.g., targeting emissions resulting from vessels connected to potential mining operations. The following sections analyze the current state of and interplay between these three regimes with a view to regulating these types of emissions and aim at identifying different legal and practical measures that would require development if mining operations were to gain momentum.

7.1 The international climate regime

Confronted with the scientific consensus that anthropogenic GHG emissions are the chief cause of global warming, which if left unabated would be dangerous to the well-being of ecosystems and humans, a concentrated international effort to address GHG emissions culminated in the conclusion of the United Nations Framework Convention on Climate Change (UNFCCC) back in 1992. The ensuing Kyoto Protocol (KP) set binding emission reduction targets on its parties through to commitment periods from 2008 to 2012 and 2013 to 2020 (KP, Article 3). As these commitments under the KP will expire at the end of 2020, States will eventually be required to reduce their GHG emissions from their so-called nationally determined contributions (NDCs) pursuant to the recently concluded Paris Agreement (PA, Article 3). To date, it appears that the topic of deep-sea mining and its potential GHG emissions is yet to be discussed in the climate context. This should come as no surprise, as deep-sea mining projects in the CCZ focus on the international seabed and its resources, a global commons that is subject to rules of non-appropriation. As such, at least prima facie, the potential GHG emissions from deep-sea mining activities at mining sites could or should rather fall within the purview of the deep-sea mining regime. Likewise, given the fact that international shipping, just like aviation, is a transnational activity involving a wide range of actors subject to differing jurisdictions, it has been agreed within the climate regime that ship emissions should better be addressed under the shipping regime. While the climate regime does not occupy the field with respect to tackling emissions from deep-sea mining activities and shipping, it is important to note that it retains some degree of oversight of all forms of emissions. Particularly those general and more specific commitments made by States under the PA will create strong political obligation to minimize GHG emissions from deep-sea mining.

7.2 The international deep-sea mining regime

Deep-sea mining activities involving the international seabed (‘the Area’) are regulated under Part XI of the United Nations Convention on the Law of the Sea 1982 (UNCLOS), an international treaty setting out various rights, responsibilities, and obligations for all activities in the Area. Article 136 of UNCLOS declares the Area and its mineral resources as the ‘common heritage of mankind’ (CHM). Essentially, this means that no States may exercise sovereignty in the Area and that the mineral resources and benefits derived from their exploitation can only be administered through a dedicated international organization. The International Seabed Authority (ISA) was established under Article 156 of UNCLOS with the mandate to design a regime to regulate deep-sea mining activities in the Area. The ISA has issued 30 exploration licenses in the Area (as of July 2019) and is currently at an advanced stage of developing regulations to govern exploitation activities (Mining Code). This effectively means that exploitation activities could, from a regulatory perspective, commence in the coming few years.

In designing regulations to develop the mineral resources in the Area, the ISA is required, pursuant to Article 145 of UNCLOS, to take necessary measures to ensure the effective protection of the marine environment from the harmful effects of deep-sea mining activities. However, even if interpreted broadly, it is unlikely that Article 145 has a climate protection objective (i.e., that it aims at protecting the climate from GHG emissions resulting from deep-sea mining activities)[4]. Thus, it comes as little surprise that most of the present regulatory discourse focusses heavily on marine environmental protection objectives. Despite that, the ISA has taken progressive and opportune steps in considering all deep-sea mining-related activities at mining sites, including GHG emissions, to be under its purview. In this regard, GHG and other chemical emissions are mentioned in the ISA's current Revised Draft Regulations on Exploitation of Mineral Resources in the Area (ISBA/25/ C/WP.1), specifically in Annex IV ('Environmental Impact Statement', under sections 4 ('Description of the physicochemical environment') and 7 ('Assessment of impacts in the physicochemical environment and proposed mitigation'). Even though the quantity of emissions does not appear to be a decisive factor in granting or reviewing an exploitation license, the ISA nevertheless requires contractors applying for an exploitation license to submit an estimation of on-site greenhouse gas emissions and their potential impacts on the environment in their environmental impact statement (EIS).

It is apparent, however, that the ISA does not include the transportation of the mineral ores from mining sites to onshore processing facilities in the assessment. Section 3 of Annex IV of the same document stipulates that: "While it is expected that this section would provide a brief description of the entire project, including offshore and land-based components, the EIS should focus on those activities occurring within the Authority's jurisdiction (e.g., activities related to the recovery of minerals from the Area up to the point of transshipment)" (Markus and Singh 2016).

[4] For broad interpretations of Article 145, see (Voeneky and Beck 2017). Note also that Article 212 (contained in Part XII of UNCLOS on the protection and preservation of the marine environment emphasizes the "need for laws and regulations to prevent, reduce and control pollution of the marine environment from or through the atmosphere."

7.3 The international shipping regime

Recognizing that shipping is a transnational activity, the global community established the Intergovernmental Maritime Consultative Organization (IMCO) in 1948, later renamed as the International Maritime Organization (IMO) in the 1970s, to regulate and standardize shipping routes and rules of navigation. A series of incidents at sea, particularly oil pollution through accidents and spills, prompted the IMO to take immediate measures to protect the marine environment. This resulted, inter alia, in the conclusion of the International Convention for the Prevention of Pollution from Ships 1973/1978 (MARPOL). The most important treaty provisions that address air pollution emissions from seagoing vessels are included in Annex VI of MARPOL, which was inserted in 1997. According to Article 3.1a and Art. 3.1b of MARPOL, the convention applies to all ships "flying the flag of a Party to the Convention" as well as those "not entitled to fly the flag of a Party but which operate under the authority of a Party." In principle, this includes vessels engaged in potential mining activities. However, Section 3.1 of Annex VI exempts those emissions directly arising from the exploration, exploitation and associated offshore processing of marine mineral resources from the requirements of Annex VI (see section 3.1.1- 3.1.4 Annex VI MARPOL). Accordingly, only those operations that are not directly linked to the on-site mining activities, including, in particular, emissions resulting from vessels commuting to and from the mining sites, are subject to the regular environmental requirements laid down in MARPOL Annex VI. Annex VI regulates emissions of gases, predominantly of SO_x and NO_x. In 2011, the Annex was expanded to additionally include GHGs. Vessels receive Engine International Air Pollution (EIAPP) Certificates when complying with NO_x regulations established by MARPOL, and the NO_x Technical Code 2008 (MEPC.177(58)). There are currently three levels of NO_x control ('Tiers') depending firstly on the vessel's construction date and secondly on the engine's rated speed. The regulations are stricter for newer ships. MARPOL currently limits the S content of fuel oils to 3.50% w/w (weight by weight). From 2020 onwards, the threshold will decrease to 0.50% w/w. In designated emission control areas (ECAs), the sulfur limits are already at 0.10%.

With reference to the case study described above, this would only affect a potential transport to Canada, as between 15% and 50% of the travel route would be located within a current ECA. In recent years, as a result of increasing pressure from the climate regime, the IMO's Marine Environment Protection Committee (MEPC) has also been trying to develop and negotiate international rules and standards to target GHG emissions from vessels. For instance, in April 2018, the MEPC adopted Resolution 304(72), entitled the 'Initial IMO Strategy on Reduction of Greenhouse Gas Emissions from Ships' with the ambition of reducing the sector's total annual GHG emissions by at least 50% by 2050 compared to 2008. Before that, it had established some measures to increase the energy efficiency of ships, including the Energy Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) (MEPC.203(62)). It is also committed to encouraging technical co-operation and technology transfer among member states in this area (MEPC.229(65)). In addition, the IMO encourages the voluntary use of the Energy Efficiency Operational Indicator (EEOI) to assist ship owners and operators with the evaluation of their fleet concerning the reduction of CO_2 emissions (MEPC.1/Circ.684). Moreover, the IMO adopted resolution MEPC.278(70) which requires ships of 5,000 gross tonnage to collect and report fuel oil consumption data to be stored in the IMO Ship Fuel Oil Consumption Database. As the IMO has started to occupy the field to regulate GHG emissions from ships, the designation of more progressive and specific regulations pertaining to this is anticipated.

8 Recommendations

Although the emissions caused by deep-sea mining operations in the CCZ will be considerably smaller than those of other maritime sectors such as international shipping, they should not be neglected, as their impacts add to already critical atmospheric GHG and pollution levels. As mining vessels do not fall under the remit of the IMO GHG and air pollution regulations, measures should be taken to minimize emissions, not only for the benefit of the environment and humankind, but also because fuel consumption, to which emissions are directly related, make up a substantial share of the mining operations flexible costs. Although the IMO's EEDI cannot directly be applied to stationary vessels, the use of energy-efficient engines can be recommended. Moreover, it may be possible to at least partially adopt the SEEMP or a similar quality management tool to optimize processes onboard, as well as the logistical concepts and need for stakeholder cooperation. Moreover, although not demanded by the IMO or the ISA at this point, it may be possible to install abatement technology to reduce emissions of individual pollutants like NO_x and SO_x, or to consider the use of alternative fuel sources. For instance, liquefied natural gas (LNG) reduces CO_2 emissions by 20–30%, NO_x emissions by 80–90%, and nearly all emissions of PM and SO_x, as LNG does not contain sulfur (Burel et al. 2013). To not diminish the benefits of using LNG, it is crucial to control CH_4 slop, which occurs if CH_4 leaves the engine unburnt. LNG infrastructure is, however, not widely available yet. For instance, Mexico currently has only three operational LNG terminals, two of which are located on the Pacific coast. New Fortress Energy, however, has recently been granted a long-term contract for building a new LNG import terminal at the Pacific coast in the Port of Pichilingue in Baja California (New Fortress Energy 2018). In Canada, there are 20 proposed LNG terminals, 14 of which will be located on the West coast (Government of Canada 2018). Nevertheless, LNG is considered a ‘fuel of the future’ and the fleet of vessels operating on LNG is constantly growing. Moreover, the sea-to-sea bunkering process for LNG is a current focus area of technology development in the international shipping sector. DNV, an international accredited registrar and classification society for ships and vessels, states that by 2020, between 400 and 600 LNG bunker vessels will operate globally (Sivadas 2017).

The choice of fuel, from an environmental, economic, and technical point of view, already needs to be considered during the early planning stages of a commercial mining operation, as LNG requires twice the storage volume compared to HFO. Another option would be to operate on marine distillate oil (MDO) or marine gas oil (MGO). This would slightly increase the CO_2 emissions but considerably decrease the SO_x and PM emissions, as the sulfur content of the fuel is considerably lower in MDO and MGO than in HFO. In fact, vessels sailing within SECAs, which currently include the North and Baltic Sea as well as the North American coastlines and are characterized by particularly strict S emission limits, often switch to MDO or MGO upon entering these designated areas. Other vessels continue to operate on HFO but install exhaust gas recirculation systems ('scrubbers') (Endres et al. 2018). These systems remove SO_x and, to a certain degree, NO_x and particles from the vessels' exhaust gas. Scrubbers can operate as open or closed loop or hybrid systems. Open loop systems use seawater to clean the exhaust gas from pollutants and discharge the acidified effluent directly into the surface water. Closed loop systems re-circulate fresh water and buffer the acidified water with sodium hydroxide (NaOH), resulting in the solid waste product calcium sulfate ('gypsum'), which in turn has to be treated on land. Although scrubber technology presents a cost-effective solution to reducing SO_x emissions, it is often criticized for shifting the problem from the air to the water column. To date, relatively little is known about the composition and biological and biochemical consequences of discharging scrubber effluents (Brynolf et al. 2014). Research does, however, indicate that the use of open-loop systems may be associated with adverse environmental impacts including the accumulation of heavy metals in the marine environment and an increase in zooplankton mortality (Koski et al. 2017). This could be particularly problematic when used in a mining vessel, which would spend an extended period of time at a specific mine site and discharge the acidified effluent in the same location.

The transport vessels fall under the remits of the IMO and need to comply with its increasingly strict regulations regarding the adoption of the EEDI and the SEEMP, as well as the reduction of SO_x and NO_x. In addition, it may be possible to reduce emission by means of slow-steaming, i.e., speed reductions, or through the optimization of travel routes. However, as the vessels involved in the transportation of marine minerals will commute between the mine site and the destination ports on an ideal route, this measure would probably not be effective in the field of deep-sea mining. Similarly, slow-steaming is viewed critically in international shipping, as slower travel speeds result in the prolongation of the voyage, which decreases the impact of the measure. For example, a change in speed of the transport vessels from the CCZ to Mexico from 14.5 to 12 knots would only reduce emissions by a factor of 1.19

due to the increase in travel time by 0.62 days. If the travel time were to remain the same, the consumption would differ by a factor of 1.46. Overall, the contribution of the transport vessels (not including bunkering vessels or other support vessels) is considerably smaller than that of the mining vessels.

9 Conclusion

Deep-sea mining will generate GHG emissions and air pollution, which will adversely affect ecosystems and humans. The exact magnitude of emissions is difficult to predict due to the unavailability and inaccessibility of commercial or experimental-scale energy demand data. Therefore, we have based this assessment on energy demand estimates provided in three different reports by Ramboll IMS and HWWI (2016), McLellan (2015), and Agarwal et al. (2012). It is important to note that it is difficult at this stage to determine which of these studies provides the most reliable demand estimates that best represent the energy demand of future commercial-scale Mn nodule mining operations. Thus, the emission levels presented here should be seen as a best estimate at this moment in time. In fact, the energy demand estimates provided in the three studies are vastly different, which is most likely related to different assumptions regarding the technical specifications of the mining equipment and mining vessels. However, the varying degree of detail with respect to the description of the technological assumptions and the partially missing references for the energy demand of individual pieces of equipment makes it difficult to clearly evaluate these differences.

In light of cumulative impacts of anthropogenic GHG emissions and air pollution, there is a need to minimize emissions levels, even if the exact quantity of emissions remains uncertain at this point. We, therefore, emphasize the urgent need to integrate emissions from deep-sea mining into the legal regimes concerned with the regulation of climate change, air pollution and shipping. Specifically, we propose that the ISA and the IMO should strengthen their cooperation to consider the implications that deep-sea mining would have in relation to GHG emissions and clarify issues of potentially overlapping mandates. In this regard, there is an Agreement of Cooperation between the IMO and the ISA, concluded in 2016, that already provides a platform for further consultation, collaboration, and coordination (see https://www.isa.org.jm/ files/documents/EN/Regs/IMO.pdf). Addressing this gap would ensure that fuel consumption and GHG emissions resulting from deep-sea mining activities are appropriately accounted for from a policy perspective. With respect to technical measures, the use of energy-efficient engines and generators, as well as the use of alternative fuels like LNG, MDO and MGO, or the installation of abatement technology should be considered to reduce emissions – even though this is not required by current regulation.

Overall, many factors will influence the levels of GHG emissions and air pollution of a commercial-scale Mn nodule mining operation, such as the annual production of the mining operation, the technological specifications of the mining vessel and equipment, the engines installed on the mining and transport vessels, the SFOC of these engines, the bunker and storage capacity of the vessels, the transport distance and speed of the transport vessels, and the time spent in different operational modes. It is, therefore, necessary to continuously update and refine the assessment of GHG emissions and air pollution, once planning advances and more detailed data becomes available. Reducing emissions is not only of interest from an environmental or sustainability-related point of view but may also from an economic perspective as fuel consumption, which is the predominant cause of emissions, makes up a considerable share of the flexible costs of deep-sea mining operations. We suggest the use of the methodology presented here for the future quantification of deep-sea mining-related air pollution and GHG emissions.

Chapter 4: Regulation of greenhouse gas emissions from deep-sea mining

Title of publication:

Regulating greenhouse gas emissions resulting from deep-sea mining in the Area

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Published in:

Unpublished draft

Abstract

Deep-sea mining will be energy intensive and cause the release of GHG emissions. Consequently, once commercial, deep-sea mining will contribute to climate change which has been identified as a 'common concern of humankind.' Currently, it is unclear how GHG emission resulting from deep-sea mining in the Area will be regulated on an international level. Considering that atmospheric GHG levels have already critical level and climate change is already affecting ecosystems and humans across the world, it is, however, imperative that deep-sea mining-related emissions need to be regulated. At first glance, three regimes appear to be generally applicable, namely the climate regime (United Nations Convention on Climate Change and Paris Agreement), the international shipping regime (International Maritime Organization and International Convention for the Prevention of Pollution from Ships), and the deep-sea mining regime (United Nations Convention on the Law of the Sea and rules, regulations and procedures adopted by the International Seabed Authority). However, a systematic assessment of the applicability and suitability of the three regimes using a criteria-based approach shows that of the three regimes the deep-sea mining regime appears to be the most promising option and should, therefore, take the lead in developing regulations to limit or reduce the sector's prospective GHG emissions. With respect to climate change mitigation, the International Seabed Authority could choose from a variety of policy instruments, including informational measures, command-and-control instruments, and market-based mechanisms.

1 Introduction

Marine mineral resources such as manganese (Mn) nodules, ferromanganese (FeMn) crusts, and seafloor massive sulfide (SMS) deposits contain significant amounts of metals which may, in the future, serve as raw material for producing a variety of commodities, including green and high-technology goods (Hein et al. 2013; Petersen et al. 2016). The current push towards the large-scale transition to a low-carbon economy and the simultaneous decline of the metal contents of terrestrial ores, to name but a few examples, have re-ignited the interest in deep-sea mining (Miller et al. 2018; Rühlemann et al. 2019; Sparenberg 2019; IEA 2021). However, the commercial exploitation of marine minerals will be associated with significant adverse environmental impacts, including the destruction of seafloor habitat, the dispersion of particle plumes in the water column, and the release of greenhouse gases (GHGs) into the atmosphere (Koschinsky et al. 2018; Weaver et al. 2018; Heinrich et al. 2020). In contrast to the former first two types of impacts, which have been subject to extensive scientific scrutiny and law and policymaking over the past years, GHG emissions from deep-sea mining operations have received comparatively little attention in both fields (Heinrich et al. 2020).

Marine mineral resources occur throughout the world's oceans. Therefore, deep-sea mining can take place on the continental shelves (including the extended continental shelves) of coastal states or in areas beyond national jurisdiction, where "the seabed and the ocean floor and the subsoil thereof" is legally referred to as 'the Area' by the United Nations Convention on the Law of the Sea (UNCLOS, Article 1(1)). The mineral resources of the Area constitute the 'common heritage of mankind' (CHM) (UNCLOS, Article 136).

Deep-sea mining operations will, broadly speaking, comprise three types of activities. The first type of activities encompasses the mining process, meaning the excavation, vertical transport, and shipboard processing of the marine minerals. As part of this process, one or more remotely operated vehicles will break and collect the ore at the seafloor. Subsequently, the ore-sediment-water mixture will be pumped upwards to the surface through a riser pipe, where it is deposited on the mining vessel, cleaned from excess sediment and water, air-dried, and stored until it is collected by a transport vessel (SPC 2013a; SPC 2013b; SPC 2013c). The second type of activity is the transportation of the ore to shore using bulk carrier vessels that will commute back and force between the mine site and a point on land. The third and last type of activities consists of the terrestrial transport and metallurgical treatment of the ore, employing vehicles, equipment, and metallurgical processing methods similar to those used to processes terrestrial mineral ores (Dames and Moore 1977; Das and Anand 2017; Boel 2018).

All three types of activities will be vastly different (i.e., mining, shipping, processing) and take place in different geographic, environmental, and legal settings. However, common to all three is that they are energy-intensive and mainly fossil fuel-based (McLellan 2015; Ramboll IMS & HWWI 2016; Boel 2018; Heinrich et al. 2020). Consequently, deep-sea mining operations will inevitably release GHG emissions and contribute to climate change, which the United Nations Framework Convention on Climate Change (UNFCCC) refers to as a ‘common concern of humankind’ (UNFCCC; Preamble, para.1) due to its many direct and indirect impacts on ecosystems, humans, the global economy, and security. Table 7 provides estimates of the GHG emissions expected to occur in conjunction with the mining, transport, and processing of 3 million t (dry weight) of Mn nodules recovered from the Clarion-Clipperton Zone (CCZ) in the central Pacific Ocean, their ship-based transport, and their processing in Mexico or Canada.

Table 7: *Overview of GHG emissions released by the three types of deep-sea mining operations based on energy demand and emission estimates published in the literature.*

Group 1 Extracting and shipboard processing*		Group 2 Ex-situ transport from the mine site to shore**			Component 3 Metallurgical processing on land***	
Reference	**Emissions (t GHG/y)**	**Reference**	**Destination**	**Emissions (t GHG/y)**	**Reference**	**Emissions (t GHG/y)**
Heinrich et al. (2020) based on Ramboll IMS and HWWI (2016)	81,000	Heinrich et al. (2020)	Mexico	30,000	Boel (2018)	153,000 - 219,000
			Canada	60,000		
Heinrich et al. (2020) based on (McLellan 2015)	135,000	Boel (2018)	Mexico	36,000	McLellan (2015)	1.2 million
			Canada	63,000		

* Hypothetical Mn nodule mining operation with an annual production of 3 million t of Mn nodules (dry weight) at 5,000 m water depth
** Transportation of 3 million t of Mn nodules (dry weight) with bulk carrier vessels
*** Metallurgical processing of 3 million t of Mn nodules (dry weight)

Likely, GHG emissions resulting from the ship-based transport of the marine minerals and their metallurgical treatment on land will be regulated like those arising from international shipping and the onshore processing of terrestrial mineral ores, respectively, due to the apparent similarities of these activities. However, if and how emissions resulting from the operation of deep-sea mining vessels and equipment in the Area will be regulated remains unclear. In fact, a recently published study confirms that it is “possible that there is a regulatory gap with respect to air emissions from activities in the Area” (ISA 2021: 52).

With the commercial exploitation of marine mineral resources in the Area on the horizon and the rapidly progressing climate change in mind, it is imperative to address and close the aforementioned regulatory gap; ideally, before the exploitation activities take place for the first time. This necessitates the consideration of three regimes, namely, climate change, international shipping, and deep-sea mining in the Area, and how these regimes intersect with each other with respect to regulating GHG emissions resulting from the excavation, vertical transport, and shipboard processing of marine minerals (type 1 activities).

More specifically, this chapter seeks to tackle two questions:

1) Which international treaty/treaties are applicable (or can be adapted to be applicable) to regulate deep-sea mining-related GHG emissions, and which among these is most suited to handle the issue?
2) Which regulatory measures could be applied to deep-sea mining-related GHG emissions under the selected regime?

It must be noted that this article focuses solely on deep-sea mining activities in the Area, assuming that coastal states will regulate GHG emissions resulting from deep-sea mining within their jurisdiction under their respective national legislations and domestic environmental policies, taking into account their commitments under international climate change law.

2 Forum choice

2.1 Introduction and methodology

This article focuses on the regulation of GHGs, a type of pollutant with known behavior (atmospheric transport) resulting from a specific type of activity (deep-sea mining, combustion of marine bunker fuels onboard of ships) in a specific legal setting (areas beyond national jurisdiction, the Area). To a certain extent, GHG emissions, atmospheric and marine pollution are already regulated under international law. For example, GHG emissions released on land and in areas under national jurisdiction are mainly covered under the UNFCCC and its related instrument, the Paris Agreement (PA), while emissions resulting from international shipping are regulated under MARPOL. Vessel-source pollution of the marine environment and the atmosphere is regulated under UNCLOS, MARPOL, and other more specific agreements. Lastly, deep-sea mining in the Area, including its environmental impacts, is regulated under UNCLOS, as modified by the 1994 Agreement Relating to the Implementation of Part XI of UNCLOS (1994 IA), as well as any rules, regulations, and procedures adopted by the International Seabed Authority (ISA). Table 8 summarizes the legal regimes involved in regulating GHG emissions, vessel-source pollution, and deep-sea mining in areas within and beyond national jurisdiction.

Table 8: *Legal regimes involved in regulating GHG emissions, vessel-based pollution, and deep-sea mining in and beyond areas under national jurisdiction.*

GHG emissions		**Vessel-based pollution**	**Deep-sea mining**	
(Mainly) national jurisdiction	*International shipping*	*National and international jurisdiction*	*National jurisdiction*	*The Area*
United Framework Convention on Climate Change Paris Agreement *(+ Domestic law)*	International Maritime Organization International Convention for the Prevention of Pollution from Ships	International Maritime Organization International Convention for the Prevention of Pollution from Ships United Nations Convention on the Law of the Sea	United Nations Convention on the Law of the Sea *(+Domestic law)*	United Nations Convention on the Law of the Sea, Part XI (as modified by the 1994 Implementing Agreement) International Seabed Authority

In our subsequent assessment of the applicability and suitability of different multilateral environmental agreements (MEA) for governing GHG emissions resulting from deep-sea mining activities in the Area, we will concentrate on these regimes. Throughout this chapter, we will refer to them as the climate regime (UNFCCC and PA), the international shipping regime (MARPOL, IMO)[5], and the deep-sea mining regime (UNCLOS and ISA). We exclude other MEAs focusing on other pollutants, activities, and sectors. We further omit MEAs with a regional geographic scope as deep-sea mining may occur in many different locations across the ocean and thus would go beyond the broad nature of the present assessment. Moreover, GHGs spread globally and affect ecosystems and humans worldwide, irrespective of where they are emitted (IPCC 2013).

In the following, we will first introduce the three legal regimes (i.e., UNFCCC and PA, IMO and MARPOL, and UNCLOS and ISA). Subsequently, we will assess their applicability and suitability concerning the regulation of deep-sea mining-related GHG emissions. In the absence of an unanimously agreed methodology (due to the very narrow focus of the article) , we have chosen an indicator-based approach to systematically assess the applicability and suitability of the three regimes, using criteria that we deem appropriate in the given context. These pre-selected criteria tie directly into the overall objective to find a practical and effective solution for limiting GHG emissions resulting from deep-sea mining in the Area (table 9). As clarified earlier, we limit our assessment to GHG emissions resulting from the first type of activities, namely the on-site extraction of minerals, vertical transport, and shipboard processing, since GHG emissions from the other two types of activities (transportation at sea and onshore processing) appear to fall squarely under the international shipping and climate regime respectively.

[5] For the purpose of this chapter, we exclude UNCLOS from the international shipping regime and cover it only under the deep-sea mining regime to avoid doubling.

Table 9: *Selected criteria to evaluate the applicability and suitability of the international climate, shipping, and deep-sea mining regime concerning the regulation of GHG emissions arising from the operation of deep-sea mining vessels and equipment in Areas beyond national jurisdiction*

Legal obstacles:
Legal obstacles are any provisions in the MEAs that explicitly prevent the application of the respective treaty to the regulation of deep-sea mining-related GHGs. For this article, legal obstacles are considered insurmountable hurdles, and the respective treaties will be excluded from further analysis.
Practical obstacles
Practical obstacles are understood here as hurdles that need to be overcome to apply the MEA to deep-sea mining-related GHGs, such as broadening the scope of the mandate of an MEA. In contrast to the legal obstacles, practical obstacles do not lead to the exclusion of the treaty but point out a need for action.
Scope:
Whether a comprehensive regime (i.e., covering a broad range of activities) or a sectoral regime (i.e., covering a single activity or sector) is more suitable to regulate a particular activity or issue depends on the activity itself and the context in which it takes place. Advantages of sectoral regimes can be their ability to include many different pollutants or impacts, a well-established work relationship, and a shared interest in a particular activity. Comprehensive regimes may, for example, be more suitable when one type of pollutant arising from many different sources needs to be regulated. In this specific case, a sectoral scope is considered beneficial.
Previous consideration of the issue:
A regime that has previously mentioned deep-sea mining-related GHG emissions demonstrates that it has recognized the issue and that the respective Parties might be interested in regulating the issue. In contrast to this, a regime that has never explicitly mentioned the issue might be unaware of it, or its Parties may not be interested in regulating it.
Regulatory reach
MEAs bind States upon their consent. Consequently, MEAs tend to rely on the national development, implementation, and enforcement of regulation and can thus only indirectly reach the actors causing the pollution in the first place. Very few MEAs or institutions play a truly administrative role and directly target public and private actors and enforce compliance with the regulations. In the context of regulating deep-sea mining-related GHGs, a more direct connection to public and private actors coupled with a stringent compliance and enforcement mechanism may be beneficial.
Flexibility in selecting mitigation measures:
Regimes with a pre-established approach to regulating GHG emissions may be somewhat static and inflexible with respect to selecting and implementing climate change mitigation measures. In contrast, regimes that have never regulated GHG emissions and have, thus, no pre-defined approach to it can choose freely from a wide variety of mitigation measures that might be particularly well suited for to regulate the activity under consideration. A regime without 'path dependency' may be beneficial in the given context.
Distribution of responsibilities
Some treaties allocate greater responsibilities to developed countries based on their more significant historic contribution to the issue and greater capacity to mitigate the issue. However, in certain contexts, this may provide an ample opportunity for polluters to evade the regulation by associating with a country with less stringent commitments. In these cases, a no-discrimination approach may be more effective for achieving a reduction of emissions.

2.2 The regimes

In the following, we will briefly present the three regimes considered in this chapter, namely the climate change regime (UNFCCC and PA), the international shipping regime (IMO and MARPOL), and the deep-sea mining regime (UNCLOS and ISA).

2.2.1 The climate regime

The ultimate objective of the UNFCCC is to "stabiliz[e] greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC, Article 2). From 16 February 2005 to 31 December 2020, the Kyoto Protocol (KP) operationalized the UNFCCC. Following a top-down approach, it established binding emission limits for developed (Annex I) countries (KP, Article 3), which were Parties to the KP during one or both of its two commitment periods from 2005 to 2012 and 2012 to 2020. The PA (191 Parties as of May 2021), adopted on 12 December 2015 and effective as of 4 November 2016, succeeded the KP. In contrast to its predecessor, the PA adopted a hybrid approach. On the one hand, it allows all countries to self-determine their climate change mitigation efforts, strongly emphasizing that these should contribute to avoiding exceeding the 1.5°C or 2°C temperature goal and become increasingly ambitious over time (bottom-up). On the other hand, it established a strict compliance mechanism, which requires the regular submission of ambitious nationally determined contributions (NDCs), progress reports and national GHG inventories, and regular global stocktakes to ensure accountability and transparency (top-down) (Bodansky et al. 2017).

2.2.2 The shipping regime (IMO and MARPOL)

The IMO, established on 6 March 1948 as Inter-Governmental Consultative Organization (IMCO), is the UN's specialized organization for international shipping and responsible for ensuring the safety of international shipping and protecting the marine environment from vessel-based pollution (IMO 2019). The latter aspect is covered under MARPOL, which presently contains six technical annexes focusing on different types of pollution, including oil (Annex I), noxious liquid substances in bulk (Annex II), harmful substances carried by sea in packaged forms (Annex III), sewage (Annex IV), garbage (Annex V), and air pollution (Annex VI). Upon its adoption in 1997, Annex VI of MARPOL mainly focused on air pollution (i.e., SO_x and NO_x emissions) (IMO 2021). However, its scope was broadened in 2011, when the IMO's Marine Environmental Protection Committee (MEPC) adopted 'Resolution 8 on CO_2 emissions from ships,' which established the IMO's GHG-related mandate. Following a global stocktake of the international shipping sector's GHG emissions in 2000, MARPOL implemented several mandatory and voluntary GHG mitigation measures to limit the sector's overall GHG emissions (Resolution MEPC.203(62) on Inclusion of Regulations on Energy Efficiency of Ships in Annex VI of MARPOL). These include the Energy Efficiency Design Index (EEDI) (MARPOL, Annex VI, Regulations 20 and 21), the Ship Energy Efficiency Management Plan (SEEMP) (MARPOL, Annex VI, Regulation 22), and the Energy Efficiency Operational Index (EEOI). A mandatory fuel data collection system (effective as of 1 March 2018), which obligates ship operators to report fuel consumption information to the IMO via the flag state on an annual basis, complements the measures. The fuel data collection system acts as a source of information on the development of fuel consumption and, consequently, GHG emissions to monitor the sector's progress towards mitigating climate change. The IMO adopted the Initial GHG Strategy on reduction of GHG emissions from ships in 2018 (IMO 2018; Joung et al. 2020)

2.2.3 The deep-sea mining regime (UNCLOS and ISA)

Adopted on 10 December 1982 and entered into effect on 16 November 1994, UNCLOS defines the rights and responsibilities of states concerning their use of the ocean and its resources. It subdivides the world's oceans into several maritime zones over which states can claim or exercise varying degrees of sovereignty or sovereign rights, as well as areas where they may not. Moreover, it establishes regulations and guidelines for protecting the marine environment and managing marine resources. Deep-sea mining in the Area is primarily regulated under Part XI of UNCLOS ('the Area') and the corresponding 1994 Agreement relating to the Implementation of Part XI ('1994 IA'). In the Area, where marine minerals constitute the current heritage of mankind (CHM) (UNCLOS, Article 136), the ISA is responsible for developing, implementing, and enforcing a sound legal framework, which regulates the exploration and exploitation of the mineral resources (UNCLOS, Article 157) and simultaneously ensures the protection of the marine environment from the adverse impacts of mining-related activities (UNCLOS, Article 145).

Thus far, the ISA has issued three sets of regulations concerning the exploration for Mn nodules (2010 and revised 2013, ISBA/19/C/17), FeMn crusts (2012, ISBA/18/A/11), and SMS deposits (2010, ISBA/16/A/12 Rev.1). It has also issued several sets of recommendations, including, for example, the 'Recommendations for the guidance of contractors for the assessment of the possible environmental impacts arising from the exploration of marine minerals in the Area' (ISBA/25/LTC/6/Rev.1). The ISA is currently negotiating regulations that would enable exploitation activities, which is currently reflected in an advanced draft version from 2019 (ISBA/25/C/WP.1) and subject to stakeholder consultation (ISA 2020). In the Area, deep-sea mining can either be carried out by 'the Enterprise' or by "State Parties, or state enterprises or natural or juridical persons who possess the nationality of State Parties or are effectively controlled by them or their nationals" (UNCLOS, Article 153 (2)(a) and (b)). [6]

As of December 2020, the ISA has entered into 30 exploration contracts with contractors granting them exclusive rights to explore dedicated areas of the international seabed (ISA 2019). All contractors need to be either a State Party or sponsored by one or more State Parties to UNCLOS (UNCLOS, Article 153(2)(b)). UNCLOS obligates these so-called sponsoring States to ensure that the contractors under their sponsorship comply with the terms of their contract and with the provisions of international law, as well as with the relevant national laws and requirements stipulated by the sponsoring State(s) (UNCLOS, Article 139 (1) and ITLOS 2011). Until now, there have been no applications for exploitation contracts.

2.3 Applicability and suitability of the different regimes

Moving forward, we will evaluate the applicability and suitability of the three legal regimes for regulating GHG emissions resulting from the excavation, vertical transport, and shipboard processing of marine minerals (type 1 activities) by testing them against the criteria listed in table 9.

2.3.1 Legal obstacles

The climate regime

Neither the UNFCCC nor the PA formally prevents the application of the MEAs to deep-sea mining-related GHG emissions. Because of this, we will consider both MEAs in the further assessment of the regimes.

The international shipping regime

MARPOL clearly states that any provisions on the regulation of GHG emissions from international shipping do not apply to deep-sea mining and related activities. These include "emissions associated solely and directly with the treatment, handling or storage of seabed minerals," and "emissions from diesel engines […] solely dedicated to [their] exploration, exploitation and associated processing"

6 The Enterprise is the ISA's independent entity for extracting, transporting, processing and marketing marine mineral resources (not yet existent).

(MARPOL, Annex VI, Regulation 19(c) and (d)). Although it is theoretically possible to amend Annex VI of MARPOL, we consider this unlikely because of the explicit exclusion of these activities and, therefore, exclude the international shipping regime from the assessment.

The deep-sea mining regime

UNCLOS does not explicitly mention the regulation of GHG emissions, which can likely be attributed to the fact that it was negotiated before climate change was recognized as a 'common concern of humankind.' However, several scholars have argued that GHG emissions can be included in the notion of 'pollution of the marine environment' under UNCLOS and covered, inter alia, under Article 212, which addresses 'pollution from or through the atmosphere' (Doelle 2006; Boyle 2012; Shi 2016). The ISA, which receives its mandate from UNCLOS (as modified by the 1994 IA), has, thus far, not explicitly recognized GHG emissions as one of the impacts it is mandated to regulate. Nevertheless, neither UNCLOS nor the ISA explicitly precludes the regulation of GHG emissions under its auspices, which warrants the further consideration of the regime in this assessment.

2.3.2 Practical obstacles

Following the exclusion of the shipping regime in section 2.3.1 of this chapter, only the climate regime and the deep-sea mining regime will be analyzed further with respect to potential practical obstacles that may complicate the regulation of deep-sea mining-related GHG emissions under their auspices. Practical obstacles point out a need for action but do not lead to the exclusion of MEAs from the assessment.

The climate regime

Under the climate regime, the most apparent complicating factor is allocating emissions to individual countries. As mentioned in section 2.2.1 above, the UNFCCC and the PA rely on their Contracting Parties to develop, implement, and enforce suitable climate change mitigation measures within their jurisdiction. Consequently, emissions need to be allocated to the Contracting Parties, which is usually done based on the location of where the emissions are released. Where emissions are released in areas beyond national jurisdiction, the allocation of emissions is more complicated (Heitmann and Khalilian 2011; Rahim et al. 2016; Cowing 2017). For instance, Heitmann and Khalilian (2011: 683) point out that "ships can be owned by a company based in one country, whose owners are citizens of another country; it can be registered in another country (its flag state) and be operated by a company that is based in yet another country." The Parties to the UNFCCC had previously encountered this problem in the mid-1990s when they attempted to regulate GHG emissions caused by international shipping (FCCC/SBSTA/1996/9/Add.2). Table 10 shows an overview of allocation options contemplated at the time.

Table 10: *Possible options to allocate GHG emissions resulting from international shipping proposed by the UNFCCC in its 1996 National Communication by the Subsidiary Body for Scientific and Technological Advice (SBSTA).*

Possible GHG allocation options discussed in the context of international shipping*
1. No allocation
2. Allocation to Parties in proportion to their national emissions
3. Allocation to Parties according to the country where the bunker fuel is sold
4. Allocation to Parties according to the nationality of the transporting company, the country where the aircraft is registered, or the country of the operator
5. Allocation to Parties according to the country of departure or destination of an aircraft or vessel. Alternatively, the emissions related to the journey of an aircraft or vessel could be shared between the country of departure and the country of arrival
6. Allocation to Parties according to the country of departure or destination of passengers or cargo. Alternatively, the emissions related to the journey of a passenger or cargo could be shared by the country of departure and the country of arrival
7. Allocation to Parties according to the country of origin of the passenger or owner of the cargo
8. Allocation to the Party of emissions generated its national space

* The options were supposed to be evaluated based on 1) “the data required to implement different options,”
2) “the need for methodologies,” and 3) “the relationship of the options to possible policies and measures, such as taxes, standards and voluntary agreements.” (FCCC/SBSTA/1996/9/Add.2)

Because they failed to reach consensus on a feasible allocation option, the Contracting Parties to the UNFCCC concluded that the activity was too complex and involved too many actors to be regulated under the UNFCCC. Instead, they decided to pass on the responsibility to the IMO as the UN’s specialized sectoral organization for international shipping. The KP confirmed this later by stating that Annex I countries “shall pursue limitation or reduction of emissions of greenhouse gases not controlled by the Montreal Protocol from […] marine bunker fuels, working through the […] International Maritime Organization” (KP, Article 2.2). The PA does not mention international bunker fuel emissions at all, which has been interpreted as re-emphasizing the role of the IMO in mitigating the sector’s GHG emissions (Martinez Romera 2016). The integration of GHG emissions caused by deep-sea mining in the Area into the climate regime would also require allocating emissions to individual countries. While this would also be complex, the actors may be easier to identify than in the case of international shipping. Moreover, due to their affiliation with a sponsoring State, they could be allocated more easily than international shipping emissions. Alternatively, emissions could, for example, be allocated according to nationality of the contractor, or the flag state of the mining vessel. The allocation of emissions based on bunker fuel sales, which is common practice under the UNFCCC (for reporting purposes only, not for regulation) (IPCC 2006), may be more controversial, as GHG emissions would then be allocated to a very small number of countries which happen to be located in the vicinity of designated mining areas, but which might otherwise not engage in the mining operations themselves (e.g., Mexico, which is located closest to the designated Mn nodule mining areas in the CCZ).

The deep-sea mining regime

As pointed out in section 2.3.1. of this chapter, neither UNCLOS nor the ISA mentions the term 'GHG emissions.' It may, thus, be necessary for the ISA to broaden the scope of its environmental mandate to add a climate protection objective. This is not far-fetched. Firstly, as pointed out in section 2.3.1, GHG emissions may be included in the notion of 'pollution of the marine environment.' Since Article 209 of UNCLOS prescribes that "rules, regulations and procedures shall be established in accordance with Part XI to prevent, reduce, and control *pollution of the marine environment* from activities in the Area" (emphasis added), this would also warrant the integration of deep-sea mining-related GHG emissions in any rules, regulations, and procedures put forward by the ISA. Secondly, although GHG emissions would not directly affect the seafloor and the water column, which is the primary focus of the ISA under Article 145 of UNCLOS, they would do so indirectly by contributing to climate change and, thus, negatively affect the marine environment by increasing the ocean's temperature and acidity (Sweetman et al. 2017; IPCC 2019). Thirdly, the release of GHG emissions would be a direct consequence of the fuel combustion onboard the mining vessels, which is a prerequisite to carrying out the 'activities of the Area' and arguably should fall within the scope of the ISA's environmental responsibility (Heinrich et al. 2020). Lastly, the recently published ISA Technical Study No. 25 states that "it is conceivable that the reference to 'operation of installations [in the Seabed Dispute Chamber's (SDC) 2011 Advisory Opinion on the Rights and Obligations of Sponsoring States] includes emissions from their operation", although the Advisory Opinion itself did not explicitly mention GHGs (ISA 2021).

2.3.3 Previous consideration of the issue

The climate regime

The UNFCC urges its Contracting Parties to prepare their national GHG inventories and national communications according to the 2006 IPCC Guidelines for National GHG Inventories ('2006 IPCC Guidelines') (Decision 24/Cp.19, para 6; UNFCCC Article 4(1)(a)). The 2006 IPCC Guidelines, which represent "the most recent scientific methodologies available to estimate emissions by sources and removals by sinks of GHGs" (FCCC/SBSTA/2009/3, para. 98), contain a comprehensive list of economic activities and sectors that can be understood as those comprised in the notion of “all economic sectors” (UNFCCC, Article 3(3)) and “all relevant sectors” (UNFCCC, Article 4(1)(c)). Until now, neither the 2006 IPCC Guidelines nor any other documents (decisions and otherwise) issued by the UNFCCC, or its related instruments, explicitly mention deep-sea mining-related GHG emissions anywhere. This may imply that the Parties are either unaware of the issue, assume it will be regulated outside the UNFCCC, do not acknowledge it as a relevant problem, or are not interested in assuming responsibility for its regulation.

The deep-sea mining regime

The ISA has previously addressed GHG emissions, albeit to a limited extent. The ‘Discussion Paper on the Development and drafting of Regulations on exploitation for mineral resources in the Area (‘Environmental matters),’ for example, mentions deep-sea mining-related GHG emissions. There, Annex III (‘Format/ Content of an Environmental Management and Monitoring Plan’) identifies “procedures to minimize greenhouse gas emissions (as defined by the IPCC)” as one of the points to be addressed in the regulations. Greenhouse gas emissions are further included in the 2019 version of the ‘Draft regulations on Exploitation of Marine Mineral Resources in the Area’ (ISBA/25/C/WP.1), where Annex IV (‘Environmental Impact Statement’) suggests a template for the outline and content of environmental impact statements (EIS) to be submitted to the ISA by contractors when applying for the permission to exploit marine mineral resources in the Area. The template briefly mentions GHG emissions as something to be included in the ‘description of the physicochemical environment.’ While it must be noted that, until now, these are merely descriptive requirements and not decisive in the evaluation and approval of exploitation applications, the ISA seems to demonstrate a certain awareness and open-mindedness about the issue.

2.3.4 Scope

MEAs can have a comprehensive (i.e., broad) or sectoral (i.e., narrow) scope. In line with Bodansky (2007), the former is understood here as a treaty that regulates a specific (type of) pollutant or impact arising from multiple sources, while the latter focuses on regulating several (types of) pollutants or impacts caused by a single activity or sector. Which of these is more suitable usually depends on the specific context of the activity to be regulated.

The climate regime (comprehensive regime)

The UNFCCC and its related instruments are examples of MEAs with a comprehensive scope, as they cover GHG emissions from virtually all sectors (most prominent exceptions: international shipping and aviation). According to Article 4(1)(c) of the UNFCCC and the 2006 IPCC Guidelines, the energy, transport, industry, agriculture, forestry, and waste management sectors are considered relevant in this regard. Because of their broad scope, the UNFCCC and PA limit themselves to defining overarching policy objectives, providing common definitions, setting up basic institutional frames, and implementing compliance mechanisms to track their Parties' progress towards meeting their climate change mitigation objectives, and ensure transparency and accountability. Both treaties leave it entirely to their Contracting Parties to select, implement, and enforce specific climate change mitigation measures as they see fit. This comprehensive approach is undoubtedly beneficial in the context of the climate change regime for several reasons: 1) a comprehensive treaty ensures global coverage; 2) due to the sheer number of GHG emitting activities, negotiating sector-specific regulations for a multitude of sectors would be economically and administratively unfeasible; 3) allowing countries to select mitigation measures is usually the most cost-effective solution and 4) developing sectoral treaties in this dimension would interfere considerably with the national sovereignty of the Parties (Bodansky 2007). However, considering that neither the UNFCCC nor the PA obligates their Parties to reduce emissions from each and every activity, there is a risk that certain activities remain entirely unregulated, should the Parties decide to focus their attention elsewhere. For example, a State could implement mandatory climate change mitigation measures in one sector but neglect emissions arising from another. Although generally possible, streamlining sector-specific climate change mitigation efforts across all nations would be very challenging and time-consuming under a regime with a comprehensive scope.

The deep-sea mining regime

The ISA is a sectoral organization that focuses solely on one type of activity (the exploration and exploitation of marine mineral resources) but can regulate different kinds of environmental impacts. Sectoral agreements can apply any type of mitigation measures its Contracting Parties consider appropriate in the given context (Bodansky 2007). Because of this, sectoral agreements can provide a harmonized approach to regulation to ensure the effective reduction of emissions from a particular sector while at the same time creating a level playing field by equally applying regulations to all actors (Bodansky 2007). Furthermore, integrating an additional impact in a regulatory framework that already addresses other environmental impacts arising from the same activity is often perceived as a practical solution. The extension of Annex XI of MARPOL, which had prior to 2011 concentrated on the regulation of NO_x and SO_x emissions is a prime example. Reasons for covering multiple impacts under one regime may include the fact that sectoral regimes have often accumulated substantial expertise and experience on the regulation of a particular activity and formed well-established work relationships and networks in the field. Furthermore, regulating several impacts under one regime (one-stop-shop) may be perceived as more practical than addressing different impacts under different regimes.

2.3.5 Flexibility with respect to selecting climate change mitigation measures

Considering that the negotiation of MEAs is usually a long and tedious process, it is to be expected that regimes with an established approach to addressing climate change mitigation will likely also apply this approach to any new activity covered under its auspices. Consequently, there is limited flexibility in selecting activity-specific climate change mitigation measures.

The climate regime

In the case of the UNFCCC and PA, the integration of deep-sea mining-related GHG emissions would likely entail the extension of the list of activities comprised in the 2006 IPCC Guidelines. Subsequently, the Parties could integrate them in their NDCs and include them in their National GHG inventories and progress reports. Here, the allocation of the emission would be critical to determine which countries would have to assume responsibility for mitigating deep-sea mining emissions. While the adoption of sector-specific measures is generally also possible under the climate regime as for example, in the case of REDD+), this appears to be a rare exception.

The deep-sea mining regime

As neither UNCLOS nor the ISA has a pre-established approach to climate change mitigation, the Parties to the ISA could choose from a wide variety of climate change mitigation measures and tailor them to meet the unique characteristics of the deep-sea mining sector. The IPCC generally recognizes three broad categories of regulatory instruments (informational measures, command-and-control instruments, and market-based measures (IPCC, 2014, AR5), which will be further discussed in section 3 below.

2.3.6 Regulatory reach

International law binds State Parties upon their consent. It applies primarily to states and not to private actors, although the latter are usually the targets of the regulations (Bodansky 2010). MEA's thus rely on national implementation and enforcement.

The climate regime

The UNFCCC and the PA rely on their Parties to select, implement and enforce climate change mitigation measures to meet the policy objectives, which they, however, complement with a stringent compliance mechanism, consisting of extensive measurement, reporting, and verification requirements to monitor compliance and ensure transparency and accountability (UNFCCC 2021). Hence, unless the UNFCCC and PA were to adopt a sectoral approach to regulating GHG emissions from deep-sea mining, which is unlikely, neither treaty would have direct control over the implementation of specific mitigation measures.

The deep-sea mining regime

In contrast to most international treaties and institutions, the ISA is an international administration (Wolfrum 2008). It exercises both legislative and executive functions and is equipped with a dispute settlement mechanism, the Seabed Disputes Chamber (SDC) of the International Tribunal for the Law of the Sea (ITLOS), that is accessible for both public and certain private actors involved in the exploration and exploitation of marine mineral resources in the Area (Wolfrum 2008). In terms of monitoring compliance, Article 153(5) of UNCLOS provides the ISA with "the right to take at any time any measures provided for under [Part XI] to ensure compliance with its provisions and the exercise of functions of control and regulation assigned to it thereunder or under any contract" and states that the ISA "shall have the right to inspect all installations in the Area used in connection with the activities in the Area." Specifically, the ISA's Council is in charge of 'exercis[ing] control over activities in the Area" (UNCLOS, Article 162(2)(l)), which also includes the task to "establish appropriate mechanisms for directing and supervising a staff of inspectors who shall inspect activities in the Area to determine whether [Part XI of UNCLOS], the rules, regulations and procedures of the [ISA], and the terms and conditions of any contract with the [ISA] are being complied with" (UNCLOS, Article 162(2)(z)). In relation to this, the ISA's Legal and Technical Commissions (LTC) can "make recommendations to the Council regarding the direction and supervision of a staff of inspectors who shall inspect activities in the Area" (UNCLOS, Article 165(2)(m)) and "carry[…] out their functions of supervision and inspection" (UNCLOS, Article 165(3)).

In terms of the regulation of GHG emissions resulting from deep-sea mining in the Area, monitoring compliance would be comparatively easy considering that GHG emissions are a function of activity and a suitable emission factor (EF) (Penman et al. 2000; IMO 2014; Trozzi et al. 2016). Contractors could, for instance, be required to report on this via their annual reports, and the ISA could monitor compliance by collecting fuel consumption data (i.e., fuel consumption data, see Heinrich et al. 2020), for example, through inspection undertaken by a body of inspectors. Moreover, should the ISA choose to introduce energy efficiency standards comparable to those imposed by the IMO, compliance could easily be monitored by inspecting vessels at sea or in port. The ISA's own enforcement powers are, furthermore, complemented by a system of state responsibility, whereby private actors need to be sponsored by an eligible member State of UNCLOS, which bears the duty to ensure that the contractor under its sponsorship complies with the terms of its contract and with the rules, regulations, and procedures of the ISA.[7]

7 see ITLOS 2011 for an overview of the obligations and responsibilities of sponsoring states

2.3.7 Distribution of responsibilities

The distribution of responsibilities is a recurring point of discussion during the negotiations of many MEAs (Stone 2004) and centers on the question of who should bear the cost of mitigating environmental impacts. Whereas the Rio Declaration on Environment and Development (1992) bases this distinction solely on "different contributions to global environmental degradation" (Principle 7), the UNFCCC also accepts other reasons for differential treatment, including economic status, financial, administrative, and technical capabilities, and differences with respect to the countries' resource base (UNFCCC, Article 4(2)(a)). In the context of climate change law, developed countries usually tend to push for an equal application of regulations to all actors, irrespective of their economic status, while developing countries often insist that regulations should primarily apply to developed countries because of their historically more significant contribution to environmental problems and their usually superior financial and administrative capacities (Bodansky et al. 2017).

The climate regime

The UNFCCC and its related instruments apply the common but differentiated responsibilities and respective capacities (CBDR-RC) principle, whereby stricter regulations apply to industrialized countries. This is, for example, emphasized in Article 3 of the UNFCCC, which states that the "Parties should protect the climate system for the benefit of present and future generation of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities." Furthermore, Article 4 of the UNFCCC, which lays out the commitment of the Parties, grants countries the right to "tak[e] into account their common but differentiated responsibilities and their specific national and regional development priorities, objectives and circumstances" when working towards fulfilling their commitments under the UNFCCC. The differentiation between developing and developed Parties was especially apparent in the KP, which imposed binding emission reduction targets only on Annex I countries (i.e., developed countries) (KP, Article 3). The PA moved away from this to a certain extent in adding "in light of different national circumstances' to the CDBR-RC principle (e.g., PA, Article 2), which on the one hand reflects the notion of the CBDR-RC principle but at the same time "stops short of prescribing CBDR-RC in the implementation of the agreement" (Bodansky et al. 2017: 221). In contrast to the KP, it applies obligations related to climate change mitigation (e.g., the preparation, submission, and updating of NDCs) to all Parties irrespective of their economic status (e.g., PA, Article 3 and 4).

Nevertheless, many of these obligations are somewhat weakened, for example, by pointing out that "developing country Parties should continue to take the lead by undertaking economy-wide absolute emission reduction targets." In contrast to this, "developing country Parties should continue enhancing their mitigation efforts and are encouraged to move over time towards economy-wide emission reduction or limitation targets in the light of different national circumstances" (PA, Article 4(4)).

While the distinction between developed and developing countries under the climate regime is necessary to ensure global participation, it may reduce the effectiveness of emission reduction measures in sectors where regulation can easily be evaded by re-locating to or associating with a country with less stringent GHG regulations. A prime example of this is the international shipping sector, where registering vessels with so-called 'flags of convenience' (i.e., registering vessels in countries different from the ship owner's nationality) is common practice. Besides being 'tax havens' for foreign vessels, these countries often lack the administrative and financial capacity or political will to enforce stringent regulations (van Fossen 2016). Therefore, the conventions operating under the auspices of the IMO place a stronger emphasis on equal treatment. In the context of climate change mitigation, this remains controversial, as several parties to the MARPOL convention call for the Convention to respect the CBDR-RC principle enshrined in the UNFCCC even in international shipping (Chen 2021).

The deep-sea mining regime

In the case of deep-sea mining in the Area, it is apparent that the regime has been designed to move away from the CBDR principle. In its 2011 Advisory Opinion, the SDC confirmed that activities in the Area are premised on the "equality of treatment between developing and developed sponsoring States" (ITLOS 2011). Thus, rules, regulations and procedures adopted by the ISA pertaining to deep-sea mining in the Area apply uniformly to all sponsoring States irrespective of their economic status, thereby discouraging the potential proliferation of 'sponsoring states of convenience.' Specifically, the SDC states that "[e]quality of treatment between developing States is consistent with the need to prevent commercial enterprises based in developed States from setting up companies in developing States, acquiring their nationality and obtaining their sponsorship in the hope of being subjected to less burdensome regulations and controls." (ITLOS, 2011, para. 159). It further elaborates that the "spread of 'sponsoring States of convenience' would jeopardize uniform application of the highest standards of protection of the marine environment, the safe development of activities in the Area and protection of the common heritage of mankind" (ITLOS, 2011, para. 159). Considering that there are already cases where deep-sea mining companies from developed countries have formed subsidiaries based in and associated with developing countries (Casson et al. 2020), emphasizing the equal application of regulations to all actors regardless of their economic status appears to be particularly important in the context of deep-sea mining.

2.4 Synthesis

Both the climate regime and the deep-sea mining regime can accommodate the regulation of deep-sea mining-related DSM emissions under their respective frameworks, although it must be noted that there are a few potential obstacles that would have to be overcome first (e.g., the allocation of emissions under the climate regime and the broadening of the ISA's environmental mandate).

Based on the comparative assessment of the two regimes, the deep-sea mining regime appears to be preferable for several reasons. Firstly, the ISA has previously considered deep-sea mining-related emissions to a certain extent, demonstrating greater awareness of the issue. Secondly, as a sectoral organization with no pre-established approach to climate change mitigation, the ISA would be more flexible in selecting mitigation measures, which it could tailor to the specific needs of the sector. It could, furthermore, broaden its scope to further include other atmospheric pollutants, which currently also remain unregulated. Thirdly, by emphasizing the importance of equal treatment, any rules, regulations, and procedures pertaining to the regulation of GHGs by the ISA would apply to all actors. In doing so, the ISA would not only prevent the evasion of regulations and ensure the effective regulation of GHG emissions, but it would also guarantee the competitiveness of the actors engaged in the exploration and exploitation of marine mineral resources in the Area. Lastly, being an international environmental administration with substantial legislative, executive and juridical powers, the ISA has a broader regulatory reach and can target both States and private entities with its regulations.

In comparison, the Parties to the UNFCCC and its related instruments do not seem to be aware of the issue of the release of deep-sea mining-related GHG emissions, don't see a need for action, or are not interested in regulating the issue themselves. Due to the MEAs' comprehensive scope and their pre-established approach to climate change mitigation, the Parties to the UNFCCC and PA would have limited flexibility in selecting and implementing sector-specific climate change mitigation measures. Moreover, due to their limited regulatory reach and enforcement powers, the treaties rely entirely on national implementation. They would, consequently, have no direct influence on the actual implementation and enforcement of climate change mitigation measures, explicitly focusing on deep-sea mining. Furthermore, the climate regime's emphasis on the application of the CBDR-RC principle, might significantly reduce the effectiveness of GHG regulations in the deep-sea mining sector and create an uneven playing field.

Table 11: *Assessment of applicability and suitability of the climate, the international shipping, and the deep-sea mining regimes with respect to the regulation of GHG emissions resulting from deep-sea mining in the Area (green = positive, making the regime suitable choice; yellow = positive, but with limitation; red = problematic, making the regime a potentially unsuitable choice)*

Criteria	Climate regime (UNFCCC and PA)	International shipping regime (IMO and MARPOL)*	Deep-sea mining regime (UNCLOS and ISA)
Legal obstacles	No explicit prevention of regulation of deep-sea mining-related GHG emissions	Formal exclusion of GHG emissions from deep-sea mining and related activities from the provisions contained in Annex VI of MARPOL, hence exclusion from further assessment	No explicit prevention of regulation of deep-sea mining-related GHG emissions
Practical obstacles	Allocation of GHG emissions to individual countries	-	Broadening of ISA's environmental mandate to include GHG emissions
Previous consideration of the issue	No previous consideration	-	Previous consideration but to a limited extent
Scope of the MEAs	Comprehensive/broad	-	Sectoral, narrow
Flexibility with respect to selecting climate change mitigation measures	Likely application of pre-established approach, thus limited flexibility in choosing sector-specific mitigation measures	-	No pre-established approach, hence, large degree of flexibility
Regulatory reach	States, strong compliance mechanism (via measurement, reporting, and verification framework) but limited direct control	-	States and private entities sponsored by States, environmental administration with legislative and executive powers, equipped with a dispute settlement mechanism
Distribution of responsibility	CBDR-RC, differential treatment of developed and developing countries	-	Focus on equal application of regulations to prevent a system of 'states of convenience'

* For this thesis, we include only the IMO and MARPOL in the international shipping regime to avoid doubling. In reality, UNCLOS also plays an important role in the regulation of international shipping and the sector's impact on the environment.

3 Instrument choice

As stated in sections 2.3.5. and 2.4. of this chapter, the member States of the ISA would have considerable flexibility in selecting climate change mitigation measures. These could be informational measures, command-and-control instruments or market-based measures, or combinations thereof. In the following, we will present climate change mitigation measures potentially applicable to deep-sea.

3.1 Informational measures

Informational measures do not directly regulate environmental impacts but intend to influence the behavior of the actors (Magat and Viscusi 1992; Bodansky 2010). On the one hand, they aim to make polluters aware of their contribution to the problem. On the other hand, they intend to increase accountability by sharing information about the actors' contributions to the problem transparently with other actors, thereby incentivizing them to improve their performance (IPCC 2007; IPCC 2014; Bodansky et al. 2017; Kieß 2018). In the context of deep-sea mining, potentially suitable measures could be the inclusion of the issue in environmental impact assessments (EIAs) (more likely as a descriptive rather than a decisive criterion) that prospective contractors have to submit to the ISA when applying for exploration and exploitation licenses, and the integration of deep-sea mining-related GHG emissions in a reporting system.

3.1.1 Environmental impact assessments

Including GHG emission in the EIAs prospective contractors must prepare for the ISA forces actors to review their actions, quantify their impact, and share this information publicly. EIAs are already a central component of deep-sea mining regulations (Durden et al. 2018; Clark et al. 2019) pursuant to Article 206 of UNCLOS. In line with this, the SDC confirmed that EIAs form part of the sponsoring States' obligation of due diligence (ITLOS 2011). As stated in section 2.3.3. of this chapter, climate change has already been suggested to be included in the template for the preparation of EIAs. It would likely be easily possible to extend the requirement to address the issue further, for example, by obligating Contractors to include information on their prospective annual GHG emissions.

3.1.2 Reporting requirements

The ISA could also require the contractors via the sponsoring States to submit information on their GHG emissions via the annual reports to increase accountability and monitor the sector's overall contribution to climate change. Once deep-sea mines become operational, it would, furthermore, be possible to obligate contractors to report regularly on their emissions to gather information about the sectors' contribution to global GHG emission levels and monitor progress with respect to emissions reductions over time.

Overall, informational measures constitute the least invasive type of regulation, as they do not impose restrictions on the actors. However, while they help raise awareness, they may not lead to concrete action (IPCC 2007; Bodansky 2010). For instance, it appears unlikely at the moment that the ISA will rely on this factor when assessing whether or not to approve a plan of work. Neither does it seem like the ISA will take action against contractors for their emissions, nor will it actively seek to require contractors to reduce emissions. Despite their limited environmental effectiveness, informational measures can complement the other types of measures and can be used to increase their environmental effectiveness (IPCC 2007; Bodansky et al. 2017).

3.2 Command-and-control instruments

Command-and-control instruments are top-down measures that an authority or regulator imposes onto the actors. They are typically complemented with monitoring, reporting, and inspection regimes, as well as sanctions or other forms of liability, to apply in case of non-compliance (Lee 2009; Kieß 2018). The most common command-and-control instruments are technical and process standards and performance standards.

3.2.1 Technical and process standards

Technical or process standards prescribe the use of a specific technology or concern the operation of a vessel or installation. Many MEAs also prescribe the general obligation to apply 'best available techniques' and 'best environmental practices' (Kieß 2018). In the context of deep-sea mining, the ISA could, for example, prescribe the installation of a particularly efficient ship engine or the use of a specific fuel type. While this would certainly be environmentally effective, it may not present the most cost-effective solution for the Contractors. Moreover, it may discourage further technological development. The ISA has already internalized the application of the 'best available technology' and 'best environmental practices' principles, although seems not entirely clear what these exactly entail. Moreover, the SDC has confirmed the responsibility of all sponsoring States with respect to ensuring their application (ITLOS 2011).

3.2.2 Performance standards

Performance standards usually prescribe emission limits, which must not be surpassed (IPCC 2007; Bodansky 2010; Kieß 2018). The EEDI implemented under MARPOL for newly built ships above 4,000 gross tonnage and the IMO's NO_x and SO_x emission limits are examples of such standards (Joung et al. 2020). The ISA could follow the example of MARPOL and adopt similar energy-efficiency standards for deep-sea mining vessels. However, considering that the EEDI is designed for moving vessels (calculated based on capacity miles) (Resolution MEPC.308(73)), the standard would have to be adapted to apply to the platform-like deep-sea mining vessels.

The draft regulations on exploitation of marine mineral resources in the Area (ISBA/25/C/WP 1) require that the organs of the ISA develop certain standards and guidelines to support the implementation of regulations. While the standards will generally be legally binding for the contractors, the guidelines will be recommendatory. In 2019, during its 25th session, the Council requested the LTC to begin with developing these standards and guidelines as a matter of priority. Since then, the ISA has made available a series of draft standards and guidelines focusing, inter alia, on the establishment of environmental baselines, the preparation of environmental impact statements, and the development of environmental management and monitoring plans for stakeholder consultation on its website (ISA 2021b). The ISA could, for example, integrate the requirement or recommendation to install energy-efficient ship engines, adhere to maximum emission levels, and use a certain type of fuel in the aforementioned standards and guidelines.

3.3 Market-based measures

Market-based mechanisms aim to incentivize actors to reduce their GHG emissions, assuming that these emissions are 'externalities,' which means that they are not reflected in a market price (IPCC 2007; Bodansky 2010). By putting a price tag on them and internalizing the externalities, the GHG emissions would be subjected to market forces, and actors would automatically strive to reduce their emissions as this would bring financial gain. The most common market-based mechanisms are emission trading schemes (ETS), carbon crediting schemes, and climate levies (Bodansky 2010).

3.3.1 Emission trading schemes

Emission trading schemes typically set an overall emission limit ('cap') and distribute or sell emission allowances to the participants accordingly. The participating actors can choose whether they want to reduce their emissions and sell off their surplus allowances or whether they want to purchase additional allowances from other actors to be able to continue on a business-as-usual path (Bodansky 2010). In the context of deep-sea mining, ETS would likely be inapplicable or at least impractical as the sector will likely involve too few actors to create a sector-specific ETS, and the integration in existing ones with a broader scope would probably be challenging.

3.3.2 Carbon crediting schemes

Carbon crediting systems distribute certified emission reductions to actors who have verifiably managed to reduce their emissions below a pre-determined baseline. Crediting systems often allow participants to achieve emission reductions through carbon offsetting, i.e. by compensating for their emissions by purchasing carbon credits produced elsewhere (Hyams and Fawcett 2013). Governments, organizations, companies, and individuals can offset GHG emissions on the voluntary carbon market either directly or via brokers who manage the investment. Whether carbon offsetting can be considered effective in terms of reducing emissions is contested. While some consider it a useful measure to reduce emissions, given that the price level of the eligible offsets is sufficiently high and that mitigation projects lead to a verifiable reduction of emissions, others view it as a means to improve the reputation of polluters and encourage them to stay on a business-as-usual path (Hyams and Fawcett 2013; Kachi et al. 2019). In terms of carbon crediting, the ISA could, for example, require contractors to offset a portion of their GHG emissions or motivate them to voluntarily offset their emissions beyond a specific limit by offering some sort of financial incentive for model behavior. The ISA could likely also take over the coordination of a sector-wide offsetting initiative. In doing so, it would also retain complete control over the quality and environmental effectiveness of the chosen mitigation projects. A coordinated approach would likely also reduce the administrative costs associated with the measure as no individual actor would have to engage with carbon markets directly (Kachi et al. 2019).

3.3.3 Climate levy

Climate levies usually take the form of taxes or fees, which are determined by the regulator (Parry et al. 2018). In the context of deep-sea mining, they could, for example, be based on fuel consumption per time or quantity of mined ore. By regularly increasing the levy charges, the ISA could motivate contractors to increase the energy efficiency of their vessels and stimulate continuous technological development. Furthermore, a climate levy would generate revenue, which the ISA could invest into monitoring and inspection activities or funding research and development efforts, including the design of technological and operational measures and the potential use of alternative fuels (Kachi et al. 2019).

3.4 Synthesis

The ISA has considerable flexibility in selecting suitable climate change mitigation measures for the deep-sea mining sector. However, in practice, this will strongly depend on the agreement of the Parties, which may be increasingly difficult to gain as we move from informational measures to command-and-control instruments to market-based measures. Agreeing on informational measures, especially if these were limited to broadening the knowledge base and not entail any form of hard consequences, would likely be comparatively easy. However, on their own, informational measures would be rather ineffective. They may, thus, be better suited as a complementary measure. Command-and-control instruments would likely be more effective and provide the ISA with direct control over the sector's GHG emissions. They could probably be easily incorporated in the standards and guidelines put forward by the ISA. In developing a suitable approach, the ISA could be guided by the standards implemented under MARPOL, although these would have to be adapted to apply to deep-sea mining vessels. The development of market-based mechanisms under the deep-sea mining regime would likely be more challenging. Moreover, gaining the necessary acceptance among the Parties may be particularly difficult, as taxation may be seen as a 'sovereign act.' All in all, this topic urgently needs to be explored in greater detail and should involve the thorough evaluation of the different policy instruments in the deep-sea mining context based on criteria, such as environmental effectiveness, cost-effectiveness, fairness, and institutional feasibility.[8]

[8] These criteria are, for example, applied by the IPCC to evaluate the suitability of climate change mitigation measures (IPCC 2007).

Table 12: *Overview of possible options for climate change mitigation measures to be adopted under the deep-sea mining regime*

Informational measures	Command-and-control instruments	Market-based mechanisms
Integration of GHGs in EIAs (i.e., anticipation of GHG emissions by the contractor prior to application for exploration and exploitation licenses)	Technical and process standards (e.g., prescription of GHG-related technology requirements such as the use of particularly energy-efficient engines and/or definition of emission limits similar to the performance standards adopted under MARPOL)	Carbon crediting schemes (i.e., voluntary or mandatory offsetting of emissions by the contractors or sponsoring states either individually or coordinated by the ISA)
Reporting requirements (i.e., integration of GHG emissions in regular reports submitted to the ISA by the contractors		Climate levy (e.g., based on operating time or processed ore, administered by the ISA, revenue can be spent on offsetting emissions, or research and development with a view to decreasing the sector's GHG emissions

Acceptance by the Parties to the ISA will likely decrease from informational measures to command-and-control instruments to market-based mechanisms.

4 Conclusion and recommendations

Once deep-sea mining occurs at a commercial scale, GHG emissions released by the operation of deep-sea mining vessels and equipment will inevitably contribute to climate change. It is, therefore, imperative that the GHG emissions should be mitigated through the implementation of environmentally effective, economical, fair, and practical measures. Regulating GHG emissions resulting from deep-sea mining is not only necessary from an environmental perspective but may, in fact, also be in the interest of the contractors. Emission reduction strategies may, for example, improve the companies' reputation and lead to increased investor trust. The latter is of particular importance considering that deep-sea mining is an emerging industry, which depends on significant investments (Sharma 2011; Cardno 2016). Many funding organizations, financial institutions, and other investors increasingly include environmental performance and sustainability-related concerns in their criteria on which they base the selection of projects to support (International Finance Corporation 2012; World Bank 2013; Jones et al. 2019).

With respect to deep-sea mining in the Area, the ISA appears to be the appropriate forum to handle this issue as it could implement a harmonized approach that would apply equally to all actors. Furthermore, it would have a large degree of flexibility in choosing mitigation measures and shape them specifically for application in the deep-sea mining sector. As a sectoral organization or rather administration, the

ISA could not only develop, implement, and enforce GHG emission regulations but also cover other air pollutants, which are currently not addressed under any regime. As such, the ISA could offer a 'one-stop-shop' solution.

Even though the ISA is the most suitable forum to regulate GHG emissions from DSM in the Area, we acknowledge that decisions at the ISA ultimately lie in the hands of its member States, and as such, there may be a lack of political will to stringently regulate this aspect of its activities. In fact, this theme does not appear to be on top of the ISA's current list of priorities at the moment. Moreover, the ISA seems to be taking the shape of a weak regulator (Ginzky et al. 2020), and accordingly, even if it does decide to regulate GHG emissions, it may choose to do so in a minimal fashion, i.e., through implementing informational measures.

Be that as it may, we urgently raise this topic for further discussion and debate at the ISA. Since the ISA is the only organization that can permit mining activities in the Area, it should bear the responsibility of the consequences arising from its decisions, mainly since mining activities in the Area must be conducted for the benefit of mankind as a whole pursuant to UNCLOS. As a first step, the regulation of GHG emissions should be put on the list of the LTC as a priority matter to consider and make recommendations to the ISA Council. Next, the ISA should consider commissioning a technical study to look into the topic of GHG emissions from activities in the Area, particularly with respect to the excavation, vertical transport, and shipboard processing of the marine minerals. Such as study could provide an in-depth evaluation of the applicability and, more importantly, the costs and benefits of implementing and enforcing policy instruments. In addition, the member States of the ISA, which are all Contracting Parties to UNCLOS, may consider putting this on the agenda of the meeting of the State Parties to UNCLOS (SPLOS), which is the forum to discuss all aspects of the law of the sea and UNCLOS, and thus could also be an appropriate avenue for broader discussion. In this respect, it is important to note that the Contracting Parties to UNCLOS also are parties to the UNFCCC and its instruments, and consequently, bound to mitigate climate change and avoid catastrophic global warming by reducing GHG emissions. One immediate outcome from discussions at SPLOS could, for example, be the establishment of a task force, ideally jointly with the UNFCCC and the IMO, to determine further handling of the issue.

Chapter 5: Deep-sea mining and sustainable development

Title of publication:

Deep-sea mining: Can it contribute to sustainable development?

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Published in:

Book Series "Transitioning to Sustainability", Volume: Sustainable Life Below Water Anna-Katharina Hornidge and Werner Ekau (Eds), Basel (CH): MDPI. Expected date of publication April 2021.

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The published article is available at: at:

https://res.mdpi.com/bookfiles/edition/1405/article/3415/p_classMDPI12titlespan_stylecolor_windowtextDeepSea_Mining_Can_It_Contribute_to_Sustainable_Developmentspanp.pdf?v=1618114039

Abstract

Deep-sea mining is increasingly suggested to meet the metal demand of the growing world population and to bring revenue and resource independence to many countries. Deep-sea mining is often also presented as a source for the metals required for the transition to a low-carbon economy. However, the exploitation of marine mineral resources will also be associated with considerable adverse impacts. Therefore, it is necessary to assess deep-sea mining impacts from a sustainability perspective and discuss if and how deep-sea mining could be compatible with sustainable development. Although deep-sea mining describes the extraction of a finite resource and, therefore, appears to contradict the Brundtland definition of sustainable development, this assessment finds that deep-sea mining could, under certain conditions, contribute to sustainable development. Important pre-requisites for this include the availability of an effective fiscal and revenue management system to ensure that the returns from deep-sea mining secure long-term benefits for national economies and stringent environmental regulations. Furthermore, environmental, and social impact assessments have to be conducted early in the process and complemented with, inter alia, sound environmental and social management plans. As the success of these measures strongly depends on the availability of trained personnel, capacity-building initiatives need to be implemented in prior or in parallel to the establishment of deep-sea mining operations. Nevertheless, there is an urgent need to explore alternatives to deep-sea mining, including the increase of recycling rates, the substitution of critical materials and an overall change of consumer behavior.

1 Introduction

Sustainable development is a kind of "development that meets the needs of the present without compromising on the ability of future generations to meet their own needs" (Brundtland 1987, para. 27). It aims at balancing economic development with human well-being and environmental conservation, taking into account concerns of inter- and intragenerational equity. The need to divert from a business-as-usual development path to a more sustainable one was re-emphasized by the international community in 2015, when all United Nations' member states adopted the 2030 Agenda for Sustainable Development ('2030 Agenda') (A/RES/70/1). The 2030 Agenda presents "a plan of action for people, planet and prosperity" (A/RES/70/1, preamble) and brings together the 2000 Millennium Development Goals (MDGs) and the climate and environment agenda rooted in the 1992 Earth Summit (Rio de Janeiro, Brazil) (BMU 2015). At the center of the 2030 Agenda are 17 interlinked sustainable development goals (SDGs) with 169 associated targets, which reflect the 2030 Agenda's objectives to "end poverty and hunger everywhere; to combat inequalities; to protect human rights and promote gender equality and the empowerment of women and girls; and to ensure the lasting protection of the planet and its natural resources", as well as the creation of "conditions for sustainable, inclusive and sustained economic growth, shared prosperity and decent work for all, taking into account different levels of national development and capacities" (A/RES/70/1, p. 3).

Whether mining is compatible with the concept of sustainable development is debatable. On the one hand, mineral resources serve as important raw materials used for the manufacture of a myriad of goods, including, inter alia, construction materials and electronic devices (UNDP and UN Environment 2018). Furthermore, the export of mineral raw materials makes up a large share of the national economies of many countries. On the other hand, mining entails the exploitation of a finite resource which is often associated with substantial environmental destruction. Furthermore, once depleted, the resource will no longer be available for future generations, as mineral deposits take millions of years to form. Due to declining ore grades, it is likely that terrestrial mines will in the future be forced to expand more rapidly both laterally and vertically to keep the production constant. Furthermore, it is expected that mines will move into more remote terrains, which taken altogether will likely intensify social and environmental pressures (Calvo et al. 2016).

Deep-sea mining, which describes the recovery of marine minerals from the deep seabed, may in the future contribute to meeting the metal demand of the growing world population (Hein et al. 2013). The idea of deep-sea mining first emerged in the 1960s, when the economic potential of marine mineral resources was widely recognized (Mero 1965; Sparenberg 2019). At that time, the interest in deep-sea mining was purely economic and geostrategic, as deep-sea mining was seen as a means to generate revenue and to decrease the dependency on foreign metal exports (Koschinsky et al. 2018; Sparenberg 2019). For a long time, the deep-sea mining narrative has, in this regard, followed the assumption that marine mineral resources are of greater value if they are exploited and converted into revenue (Christiansen et al. 2019). This is underpinned by the claim that deep-sea mining could provide the metals needed for the transition to a low-carbon economy (Hein et al. 2013; Paulikas et al. 2020). Moreover, several studies indicate that deep-sea mining may, in fact, be more environmentally friendly than terrestrial mining (Hein and Koschinsky 2014; Batker and Schmidt 2015; Koschinsky et al. 2018; Paulikas et al. 2020). However, this rather positive outlook on deep-sea mining is increasingly challenged, as concerns about the potential large-scale and long-term environmental impacts and the potential implications for humans and ecosystems are raised (Weaver and Billet 2019). Furthermore, it has been questioned whether a comparison of terrestrial and deep-sea mining is even warranted, given that there is no indication that deep-sea mining will eventually replace terrestrial mining. Instead, it is more likely that both will be carried out in parallel, ultimately intensifying environmental and social conflicts even further (Christiansen et al. 2019).

With commercial deep-sea mining on the horizon, it becomes increasingly important to explore if and how deep-sea mining can contribute to sustainable development. This requires a thorough assessment of environmental, economic, and social concerns. Following this introduction, this chapter will present the three different types of marine mineral deposits under consideration to be mined, including envisioned mining concepts, and briefly explain the legal context of deep-sea mining. Subsequently, the chapter will outline environmental, economic, and social considerations and conclude with a section on implications for sustainable development.

2 Types of marine mineral deposits

2.1 Manganese nodules

Manganese (Mn) nodules are small, potato-shaped mineral concretions, which mainly consist of concentric intergrown layers of Fe and Mn oxides, but also contain significant quantities of various metals, including Ni, Cu, Co, Mo, Zn, Pt, Te, and REEs (Hein and Koschinsky 2014). They form by precipitation of metals from seawater or sediment pore water and occur nearly everywhere on the world's oceans, but are especially abundant in the Clarion-Clipperton-Zone (CCZ), the Peru Basin, near the Cook Islands (all located in the Pacific Ocean), and the Central Indian Ocean Basin (Hein et al. 2013; Petersen et al. 2016). Most Mn nodule mining concepts envision mining operations to consist of one or more remotely operated vehicles, which will collect Mn nodules at the seafloor. From there, the Mn nodules will be pumped through a riser pipe and deposited onboard a mining vessel at the surface. Onboard, the Mn nodules will be washed, partially dried, and stored, until they are collected by a transport vessel and brought to land, where they will be metallurgically processed. The wastewater-sediment-mixture will be returned to the water column (Atmanand and Ramadass 2017; Blue Mining 2014; Hong et al. 2010; Ramboll IMS and HWWI 2016). It has been suggested that this should happen at near-seafloor depth to avoid the contamination of pelagic ecosystems (Drazen et al. 2020).

2.2 Ferromanganese crusts

Ferromanganese (FeMn) crusts form by precipitation of metals on the sediment-free summits, platforms, slopes and saddles of seamounts in water depth between 400 and 7,000 m over the course of millions of years (Hein and Koschinsky 2014). They consist of strongly intergrown sub-crystalline iron and Mn oxide layers and contain economically interesting quantities of other metals, including Ni, Cu, Co, Mo, Zr, Nb, and REEs, and reach a known maximum thickness of about 26 cm (Halbach et al. 1982; Hein et al. 1992; Lusty et al. 2018). It is believed that there are thousands of seamounts located across the world's oceans, but the Prime Crust Zone (PCZ), which stretches from the Mariana Trench to the Hawaiian Islands, is of particular interest because of its high abundance of crusts with high metal contents (Wessel et al. 2010; Lusty et al. 2018; Hein and Koschinsky 2014). Due to their firm attachment to the underlying rock, the mining of FeMn crusts is considered to be particularly challenging (Lusty et al. 2018; Koschinsky et al. 2018). In August 2020, the Japan Oil, Gas, and Mineral National Corporation (JOGMEC) announced that it conducted the world's first successful crust-mining test, during which they excavated 649 kg of FeMn crusts from the seafloor off the Japanese coast, using a FeMn crust-excavating testing machine developed by JOGMEC itself (JOGMEC 2020).

2.3 Seafloor massive sulfide deposits

Seafloor massive sulfide (SMS) deposits form in hydrothermally active areas by precipitation of minerals, where hot metal-rich hydrothermal fluids cool or get in contact with cold ambient seawater (Hannington et al. 2005). They consist mainly of metal–S compounds and contain significant amounts of Fe, Cu, Zn, Ag, and Au, as well as smaller quantities of REEs (Monecke et al. 2014). SMS deposits are located in geologically active areas such as mid-ocean ridges, and in volcanic arc and back arc basins, and at intraplate volcanoes (Petersen et al. 2016). Based on plume studies and deposit occurrence models, Hannington et al. (2011) estimated that there are between 500 and 5,000 vent fields with associated mineral deposits. Hydrothermal vent fields are considered active, while the venting of hydrothermal fluids is ongoing, inactive, and eventually extinct, when it ceases. Vents located on slow-spreading ridges (e.g., Atlantic Ocean) can last for hundreds of thousands of years whereas those located on fast-spreading riches (e.g., East Pacific Rise) often rise and fall over decades (Copley et al. 2016). Deep-sea mining of SMS deposits will likely concentrate on inactive vent sites, which have accumulated over a longer time than active vent sites (German et al. 2016; Van Dover et al. 2018). Furthermore, active venting of hot hydrothermal fluids may pose a significant threat to mining equipment (SPC 2013c). Mining concepts currently envision the combined use of different seafloor vehicles (bulk cutter, auxiliary cutter and collector), which will cut and collect the ore at the seafloor. From there, it will be pumped to the sea surface, cleaned from sediment onboard a mining vessel and then transported to shore for further metallurgical processing (SPC 2013c). More recently, the use of vertical cutter systems has been suggested (Spagnoli et al. 2016).

3 Deep-sea mining in areas within and beyond the limits of national jurisdiction

The responsibility of regulating the exploration and exploitation of marine mineral deposits in territorial waters, exclusive economic zones (EEZs) and the continental shelf zones lies with the respective coastal states, who are obligated by the United Nations Convention on the Law of the Sea (UNCLOS) to adopt appropriate regulations that are "no less effective than international rules, standards and recommended practices and procedures" (UNCLOS, Article 208 (3), see Section 4.3 below for information on environmental obligations of coastal states). Deep-sea mining in areas beyond national jurisdiction is primarily regulated by Part XI of UNCLOS ('the Area') and the corresponding 1994 Agreement relating to the implementation of Part XI of UNCLOS ('1994 IA'). The international seabed (termed 'the Area' by UNCLOS) and its resources constitute the Common Heritage of Mankind (CHM) (UNCLOS, Article 136), which means that the resources of the Area are vested in all humankind

(UNCLOS, Article 137 (1)), effectively prohibiting states from claiming, acquiring, or exercising sovereign rights over them (UNCLOS, Article 137 (3)). Instead, the resources of the Area are managed by the International Seabed Authority (ISA), which has been established by UNCLOS (153 (1)) and is to act on behalf of mankind as a whole (UNCLOS, 137 (2)).

The CHM principle has been established to ensure that the benefits from exploiting the resources of the Area are shared by all countries "irrespective of the geographic location of States, whether coastal or land-locked, and taking into particular consideration the interests and needs of developing States" (UNCLOS, Article 140). As such, its objective is to prevent a situation in which the benefits obtained from deep-sea mining can only be enjoyed by industrialized countries, which have the financial capacity and technical skill to carry out such expensive and risky endeavors (Jaeckel et al. 2016). Key elements of the CHM principle include (1) the exclusive use of the international seabed for peaceful purposes (UNCLOS, Article 141), (2) the principle of non-appropriation (UNCLOS Article 137 (1)), (3) the reservation of mineable areas for developing states in the Area, (4) the equitable sharing of monetary and non-monetary benefits (UNCLOS, Article 140(2)), and (5) the protection and preservation of the marine environment for the benefit of current and future generations (UNCLOS, Article 145). To this end, the ISA's main tasks include the development of a regulatory and administrative structure that allows the sharing of monetary and non-monetary benefits and the development of stringent environmental regulation, which ensures the protection and preservation of the marine environment from the impacts of deep-sea mining, taking into account concerns of intergenerational and intragenerational equity (Frakes 2003; Jaeckel et al. 2016; Bourrel et al. 2018; Joyner 1986; Kiss 1985).

Deep-sea mining in the Area can either be carried out by 'the Enterprise' (the ISA's would-be mining entity responsible for mining, transporting, processing and marketing marine minerals recovered from the Area) and, in association with the ISA, by member States of UNCLOS, state and private enterprises, natural or juridical persons who have the nationality of a member State and who are sponsored by such a State (UNCLOS Article 139). The sponsoring State is required to ensure that the contractor (i.e., the entity entering exploration or mining contracts with the ISA) complies with the terms of its contract and with the relevant provisions of international law. In this regard, the sponsoring State has an obligation of due diligence in setting and enforcing its laws and regulations, meaning that it has to adopt, implement and enforce appropriate rules and regulations (ITLOS 2011), which, according to Lily (2018: 2), may include the provision of "institutional capabilities such as an identified regulatory body, with monitoring and enforcement functions and access to appropriate personnel, equipment and other technical capacity to implement them." Whenever sponsoring States have implemented appropriate measures, they cannot be held liable for a contractor's misconduct (ITLOS 2011). As of December 2020, the ISA has entered into 30 exploration contracts, 18 of which are for Mn nodules, five for FeMn crusts and seven for SMS deposits (ISA 2020).

4 Environmental considerations

4.1 Environmental impacts of deep-sea mining

4.1.1 Biological impacts

Mn nodules

Mn nodules are loosely placed in and on top of the sediment of the abyssal plains of the oceans in an environment, which is characterized by high pressure, low temperature and very slow dynamics of (bio)geochemical processes. The nodules serve as a habitat for a variety of sessile and mobile faunal taxa (e.g., bacteria, nematodes, harpacticoid copepods, polychaeta, isopod crustaceans, holothurians, fish, corals, bryozoans, xenophyophores, and sponges), which typically feed on detritus and fecal pellets produced by zooplankton sinking down from the sea surface (marine snow) (SPC 2013a; Amon et al. 2016; Vanreusel et al. 2016; Weaver and Billet 2019). Collector vehicles moving over the seafloor will not only destroy the Mn nodules and with it the habitat for organisms using them as hard substrate, but will also stir up the sediment, effectively threatening bottom-dwelling and filter-feeding organisms (Koschinsky et al. 2018; Weaver and Billet 2019). In addition to this, the re-deposition of the suspended sediment is also expected to adversely affect these organisms, as this would likely happen at a much higher rate than natural sedimentation (Weaver and Billet 2019).

FeMn crusts

FeMn crusts provide solid substrate for sessile filter feeding taxa (e.g., corals, sponges) and a variety of mobile taxa, including echinoderms, squids, and foraminifera (Mullingneaux 1987; Clark et al. 2010; Weaver and Billet 2019). The distribution of species and the composition of communities vary depending on factors like water depth, current flow and type of substrate (Rowden et al. 2010). Research has indicated that the seamounts host considerably more biomass than the slopes of continental margins at the same depth (Rowden et al. 2010). The removal of the crusts would inevitably lead to the vast destruction of large areas of habitat. Furthermore, the mining of crusts could produce particle plumes, including re-suspended sediment and abraded crust particles. However, as seamounts will only accumulate sediment on plateaus and in fractures, the size and distribution of the particle plume will likely be much smaller than the plumes generated by Mn nodule mining (SPC 2013a; Hein and Koschinsky 2014; Koschinsky et al. 2018).

SMS deposits

SMS deposits, specifically active hydrothermal vent fields, provide unique habitats for a variety of highly specialized organisms (e.g., shrimp, tube worms and bacteria) (SPC 2013c). Many of these species are endemic to individual vents and rely on a well-functioning symbiotic relationship with certain chemoautotrophic species (SPC 2013a; Van Dover et al. 2018). Vent communities also show a zonation, meaning that the different organisms occur at different distances to the vent (Rogers et al. 2012). The impacts of SMS mining will likely be site-specific due to variations in local abiotic conditions, including substrate type, water depth, temperature, salinity and particulate organic matter supply from the surface (Boschen et al. 2016). Overall, the area affected by mining will be smaller than the area influenced by nodule or crust mining, as SMS mines would mostly extent into the sub-seafloor (SPC 2013c; Weaver and Billet 2019). However, due to the uniqueness of individual active vent habitats, the mining of active vents would risk destroying rare types of habitat. Furthermore, due to the smaller size of the deposits, more vent sites would likely have to be mined. However, it is more likely that inactive vent sites would be preferentially mined in the future, as they may provide larger ore deposits and would be technically easier to mine than active vent sites. While, here, fauna can be expected to be more similar to the ambient deep-sea fauna of the region, as the typical vent fauna can only survive at actively venting sites, the scarcity of ecological studies at inactive SMS deposits makes clear assessments of a potential environmental impact of mining difficult (Van Dover 2019). Like for active SMS deposits, the affected area of mining would be much smaller than the affected area of Mn nodule or FeMn crust mining.

4.1.2 Geochemical impacts

Deep-sea mining can also cause geochemical changes by altering the chemical equilibrium of the sediment-water interface as a consequence of the excavation of marine mineral resources and the removal of surface sediment. In the case of Mn nodule mining, the extent of the release of toxic metals from seawater and sediment pore water is believed to be small, unless mining causes particularly deep disturbances. Strong interferences could, however, occur in areas where the oxygen penetration depth in the sediment is very low. However, recent studies suggest that oxygen reaches depths of more than 1.5 m throughout the CCZ (Mewes et al. 2014; Volz et al. 2020). In the Peru Basin, where Mn nodules are also highly abundant, the oxygen penetration depth is only between 10-15 cm (Haeckel et al. 2001; Paul et al. 2018). FeMn crust mining is not expected to cause a significant release of toxic metals, as the FeMn crusts typically form under fully oxic conditions. However, mining FeMn crusts on shallow seamounts close to the oxygen minimum zone could lead to a partial redissolution of Mn oxide from crust particles and release of trace metals within the oxygen minimum zone could occur (Koschinsky et al. 2003). The mining of SMS deposits may have a substantial geochemical impact because of the high oxidation potential and reduced state of the sulfide minerals (Van Dover et al. 2020). Research has shown that even species inhabiting active vent sites, which are characterized by a comparatively high concentration of metals in the surrounding water, may be negatively affected by elevated metal concentrations due to mining (e.g., Hauton et al. 2017). Although many vent species may be more adapted to changing environmental conditions and appear to have developed strategies against metal toxicity (vent mussels, for example, store immobile metal compounds in their tissue, Koschinsky 2016), it is unclear to what extent these strategies would protect the organisms against metal release from the mining of SMS deposits.

4.1.3 Particle plumes

The operation of the collector vehicles at the seafloor and the discharge of excess sediment and water from the mining vessel will create metal-rich particle plumes close to the seafloor and in the water column, which may negatively affect benthic and pelagic ecosystems and may extend far beyond the mine site (SPC 2013a, 2013b, 2013c). Whereas early research mostly relied on hydrodynamic models to anticipate the dispersion of the plume (Jankowski and Zielke 2001; Rolinski et al. 2001), more recent experiments show aggregation effects, indicating that previous research may have overestimated the range of the plume (Gillard et al. 2019). Nevertheless, fine particles can be transported over long distances and potentially negatively affect marine organisms (Weaver et al. 2018). The mining of the slopes of seamounts and active vent sites is not expected to produce large particle plumes, as these are generally not covered with a thick sediment layer. Guyots and fractures of seamounts, as well as inactive vent sites can, however, accumulate sediment. Similarly, inactive hydrothermal vent sites may also be covered by several cm of sediment, which may be dispersed during mining and the discharge of excess water and sediment from the mining vessel (Weaver and Billet 2019; Van Dover et al. 2020).

4.1.4 Noise and light pollution

Exposure to noise and vibration resulting from mining operations can compromise the ability of marine organisms to communicate and to detect prey. As noise travels well underwater, noise pollution could affect an area much greater than the mine site (Weaver et al. 2018). Noise impacts may be particularly severe in the upper 200 m of the water column, where it may negatively affect marine mammals (Weaver and Billet 2019). Similarly, lights attached to mining equipment could disturb species that are accustomed to living in a dark environment (Popper et al. 2003; Weaver et al. 2018; Weaver and Billet 2019). Furthermore, artificial light may conceal bioluminescence, which may compromise the ability of marine organisms to navigate, mate, detect food and defend against predation. Near the vessels, artificial light may also attract organisms and disrupt their movement. Furthermore, birds may be adversely affected by the lights illuminating the working decks of the mining vessels (Weaver and Billet 2019).

4.1.5 Greenhouse gas emissions and air pollution

The combustion of fuel oil onboard the mining and transport vessels will cause the release of greenhouse gases (GHGs) (i.e., CO_2, CH_4, N_2O) and other air pollutants (e.g., CO, SO_x, NO_x, NMVOCs, PM) (IMO 2014). These emissions will contribute to global warming, acidification, and the formation of photochemical ozone (Huijbregts et al. 2016). Thus far, the impacts to air directly resulting from deep-sea mining have received little attention in science and policymaking. They should, however, be considered in a holistic assessment of the environmental impacts caused by deep-sea mining, especially in the context of climate change mitigation, and incorporated in the regulatory framework (Heinrich et al. 2020).

4.1.6 Ecosystem functions and services

The impacts caused by deep-sea mining may also affect ecosystem functions and services (Le et al. 2017; Orcutt et al. 2020; Thornborough et al. 2019). Ecosystem functions of marine ecosystems include element and nutrient cycling, the provision of breeding grounds, nursery habitats and refugia, bioturbation, dispersal and connectivity, as well as primary and secondary productivity, metabolic activity and respiration (Le et al. 2017). Ecosystem services describe the benefits humans obtain from well-functioning ecosystems and are commonly subdivided into provisioning services, regulating services, supporting services, and cultural services (MEA 2005). Provisioning services obtained from marine ecosystems include, for example, fish, shellfish, biomaterials, pharmaceuticals, and industrial agents. Regulating services include, for example, carbon sequestration, the control of pests and populations, and the storage, burial, transformation and detoxification of waste material and pollutants. Cultural services include aesthetic and spiritual value, educational services, and the notion of ocean stewardship. Supporting services include the ecosystem functions listed above (Le et al. 2017; Armstrong et al. 2012). Biodiversity is considered to be of particular importance in supporting ecosystem functions, although the relationship between biodiversity and ecosystem services is not fully understood (Balvanera et al. 2014; Bennett et al. 2015). How and to what extent deep-sea mining will affect ecosystem functions and ecosystem services is uncertain but may be significant. It should, therefore, be considered in the development of regulatory frameworks and management practices (Thornborough et al. 2019; Le et al. 2017).

4.2 The mitigation hierarchy

The mitigation hierarchy provides a systematic approach for reacting to the environmental impacts of an activity. Its main objective is to avoid net loss of biodiversity and, wherever possible, to achieve net gain. The mitigation hierarchy requires the consideration of four elements in a strict hierarchical order: (1) avoid, (2) minimize, (3) restore, (4) compensate/offset (Billet et al. 2019). Although originally developed for application in terrestrial settings, it is now increasingly applied to coastal and marine environments, including the deep-sea.

4.2.1 Avoid

The first objective of the mitigation hierarchy is to avoid deep-sea mining altogether by reducing the overall demand for metals through recycling, substituting non-renewable with renewable materials and changing consumer behavior, although it is unclear whether this would be sufficient to meet the increasing demand of the growing world population (Billet et al. 2019; Rühlemann et al. 2019). If complete avoidance of deep-sea mining is impossible, then measures should be adopted to protect certain areas from the adverse impacts of mining through the establishment of marine protected areas in which no mining can take place.

An important measure in this regard is the establishment of regional-scale environmental management plans (REMPs), which are supposed to help maintain regional biodiversity, ecosystem structures and ecosystem functions, and preserve typical regional ecosystems (Cuvelier et al. 2018; Niner et al. 2018; Jacob et al. 2016). According to Jones et al. (2019: 175), REMPs for deep-sea mining may include "an assessment of the probability, duration, frequency and reversibility of environmental impacts, the cumulative and transboundary impacts, the magnitude and spatial extent of the effects, the value and vulnerability of the area likely to be affected including those with protection status and the extent of uncertainty in any of the above.” The ISA has, until now, only adopted a REMP for the Mn nodule fields of the CCZ, whose central component is a network of nine Areas of Particular Environmental Interests (APEIs) (ISBA/24/C/3). The APEIs cover an area of 400 km × 400 km each and represent the nine sub-regions of the CCZ. The guiding principles of the CCZ REMP are listed as: (1) the CHM, (2) the precautionary approach, (3) the protection and preservation of the marine environment, (4) the requirement to conduct environmental impact assessments (EIAs), (5) the conservation and sustainable use of biodiversity and (6) transparency.

The establishment of representative APEIs is complicated by the persisting lack of knowledge about species abundances and community composition in the deep sea. There is, however, a clear call for the establishment of further REMPS (including APEIs) in the Area, including prospective sites for the mining of FeMn crusts and SMS deposits. The selection of APEIs should be guided and by a comprehensive set of environmental criteria and objectives. Moreover, Tunnicliffe et al. (2020: 3) point out that “clearly identified targets using well-defined and standardized performance indicators [are needed] to evaluate progress (or lack thereof) towards achieving desired outcomes.” However, due to the uniqueness of SMS habitats, finding representative sites for the placement of APEIs will be challenging (Koschinsky et al. 2018). Within areas of national jurisdiction, the Pacific Community established the Regional Environmental Management Framework for Deep Sea Minerals Exploration and Exploitation in cooperation with the EU (Swaddling 2016).

4.2.2 Minimize

The second objective of the mitigation hierarchy is to minimize adverse environmental impacts as much as possible via technological means. While habitat destruction by seafloor vehicles is inevitable in a deep-sea mining context, it may be possible to reduce the impact of the particle plume. For example, Niner et al. (2018) suggest the use of shrouds on seafloor vehicles to limit the production and spreading of fine particles and Cuvelier et al. (2018) mention the possibility to increase flocculation to encourage a faster settling of the plume. Furthermore, the use of alternative energy sources (e.g., LNG) and the increase of the energy efficiency of the ship engines could limit the release of GHGs and air pollutants (Heinrich et al. 2020).

4.2.3 Restore

The third objective of the mitigation hierarchy is to restore ecosystem function and services after destruction. While this is common practice in terrestrial mining, the restoration of deep-sea ecosystems is extremely difficult due to the large scale of the affected areas, persisting knowledge gaps, and limited economic feasibility (Van Dover et al. 2014; Niner et al. 2018; Billet et al. 2019).

4.2.4 Compensate/offset

The compensation/offsetting of biodiversity loss can be considered as a last option to prevent a net loss of biodiversity. This can be achieved by protecting or restoring similar habitats to those mined (‘like for like’), or to create new biodiversity of a different kind in different types of environments (‘out of kind’). Furthermore, it may be possible to compensate in an entirely different manner, for example, through investing in capacity-building initiatives. However, Niner et al. (2018) point out that ‘out of kind’ compensation can neither negate biodiversity loss nor compensate for lost ecosystem functions and should, therefore, not be considered true offsets.

4.3 Environmental regulation

4.3.1 National jurisdiction

In areas within national jurisdiction, UNCLOS obligates coastal states to ensure the protection and preservation of the marine environment (UNCLOS, Articles 192 and 193). In this regard, UNCLOS requires states to attempt "as far as practicable, directly or through the competent international organization to observe, measure, evaluate and analyze by recognized scientific methods, the risks or effects of pollution of the marine environment" resulting from activities "which they permit or in which they engage" (UNCLOS, Article 204). Wherever states suspect "substantial pollution [or] significant harmful changes to the marine environment", they are required to "as far as practicable, assess the potential effects of such activities on the marine environment and shall communicate reports of the results of such assessments" (UNCLOS, Article 206) to the competent international organizations (UNCOS, Article 205). With respect to deep-sea mining, coastal states are obligated by UNCLOS to "adopt laws and regulations to prevent, reduce and control pollution of the marine environment arising from or in connection with seabed activities subject to their jurisdiction," and "other measures that may be necessary to prevent, reduce, and control such pollution" (UNCLOS, Article 208 (1) and (2)), further specifying that "such laws, regulations and measures shall be no less effective than international rules, standards and recommended practices and procedures" (UNCLOS, Article 208 (3)). In this regard, UNCLOS, Article 194(3)(c) obligates states to minimize "pollution from installations and devices used in exploration or exploitation of the natural resources of the seabed and subsoil." This also includes the obligation of states to prevent transboundary harm arising from activities conducted in areas under their jurisdiction (UNCLOS, Article 194(2)).

Several states have already enacted specific deep-sea mining regulations or incorporated them within existing frameworks. Papua New Guinea, has, for example, incorporated provisions for deep-sea mining in its 1992 Mining Act, which, however, aims mainly at encouraging mining and contains very few environmental provisions. These are included in the 2000 Environment Act, which, for example, requires the submission of environmental impact statements (EIS) (including monitoring, environmental management programs, collection of baseline data and remediation), and Environmental Inception Reports (§51(b)). However, past experience with terrestrial mining operations, as well as the country's high level of poverty, civil conflict, inequality and poor rule of law gives rise to concern with respect to the implementation and enforcement of the regulations (Singh and Hunter 2019).

Another Pacific island state interested in hosting deep-sea mining operations within its coastal regions is Tonga, which has already issued exploration licenses to several contractors under the country's mineral and petroleum mining law (Blue Ocean Law and the Pacific Network on Globalisation 2016; Singh and Hunter 2019). In 2014, Tonga has adopted its new Seabed Minerals Act, which has been drafted with the help of the Secretariat of the Pacific Community (SPC) and the EU. Although the Seabed Minerals Act contains suitable environmental provisions, including the requirement to submit environmental impact assessments (EIAs), it is doubtful that the country will be able to implement and enforce the regulations, due to a profound lack of financial and institutional capacity (Singh and Hunter 2019).

The Cook Islands are actively seeking contractors to exploit Mn nodules within its EEZ. The country adopted its Seabed Minerals Act in 2009, which mainly aimed at facilitating mining and gave little attention to environmental concerns. The 2015 Seabed Minerals (Protection and Exploration) Regulations contained more provisions on the environment, albeit in weak language. Nevertheless, the country has implemented the Marae Moana Act in 2017, which establishes the marine protected area Marae Moana, including a 50 km no-mine zone around the country's coastline (§24).

In contrast to the small island states, New Zealand, which incorporated provisions on deep-sea mining in its 1991 Crown Minerals Act and 2012 Exclusive Economic Zone and Continental Shelf (Environmental Effects) Act, appears to place greater emphasis on the protection of the environment and has even denied a mining application because of it (New Zealand EPA 2015; Singh and Hunter 2019).

4.3.2 The Area

The ISA has already issued three sets of prospecting and exploration regulations for Mn nodules (2010, revised in 2013) (ISBA/19/C/17), FeMn crusts (2012) (ISBA/18/A/11) and SMS deposits (2010) (ISBA/16/A/12 Rev.1) and is currently in the process of developing a corresponding set of exploitation regulations. The draft regulations (ISBA/25/C/WP.1) contain requirements for the application for and approval of exploitation contracts, including the obligation to submit a plan of work, a mining plan, a feasibility report, a financing plan, a training plan, an emergency response and contingency plan, an environmental impact statement, an environmental management and monitoring plan, and a closure plan. The drafting process also included a stakeholder consultation phase, during which contractors identified gaps in the regulatory framework, including the lack of information on the operationalization of the polluter pays principle, the precautionary approach and the ecosystem approach, as well as the consideration of the impacts of climate change and cumulative effects. Furthermore, concerns were raised about the review of contractor compliance with environmental regulations and the unclarified relationship between environmental impact statements, environmental standards, and environmental management and monitoring plans. To this end, the stakeholders suggested the drafting of concrete guidelines for the preparation of EIS and environmental management, monitoring and closure plans, including the requirements for the collection of baseline data. The stakeholders, furthermore, called for the development of standards to ensure the protection of the marine environment (ISBA/26/C2). In addition to the exploration and exploitation guidelines, the ISA has issued the Recommendation for the Guidance of the Contractors for the Assessment of Possible Environmental Impacts Arising from Exploration for Marine Minerals in the Area (ISBA/19/LTC/8), which prescribes the collection of baseline data in the exploration areas employing best available technologies and to conduct EIAs before, during, and after the exploration activities. Although the recommendations are not legally binding, contractors are expected to follow them (Lodge 2015).

5 Economic considerations

Whether deep-sea mining will yield net benefits and for whom, depends on numerous factors, including the occurrence, volume and composition of the mineral deposit to be mined, the capital and operational costs required for recovering them (especially in comparison to terrestrial mining), the development of the metal market, and whether the environmental costs of mining are considered (Jaeckel 2020; Folkersen et al. 2019; Mukhopadhyay et al. 2019; Van Nijen et al. 2019). Any predictions of the future profitability of deep-sea mining are complicated by persisting knowledge gaps, a high level of uncertainty, and the general difficulty of expressing environmental impacts in economic terms (Folkersen et al. 2019; Mukhopadhyay et al. 2019; Folkersen et al. 2018b). Where deep-sea mining is carried out in the Area, the profitability of deep-sea mining may also be influenced by the compensation of terrestrial-mining countries, which are negatively affected by metals obtained from deep-sea mining entering the global market, as demanded by the CHM (Christiansen et al. 2019). According to Van Nijen et al. (2019: 579), this could likely occur with respect to the manganese market, which according to them is “shallow (low activity compared to the volume), non-transparent, and fragmented.”

5.1 National jurisdiction

Within national jurisdiction, states expect to benefit from hosting deep-sea mining operations in two ways: 1) by receiving royalties from the contractors in exchange for the right to exploit the country's mineral resources, and 2) by collecting corporate income tax (Mullins and Burns 2018). Particularly small island states appear to have high hopes to generate revenue for their economies by encouraging the development of a deep-sea mining industry. Although the economic benefits may be substantial given the countries low number of inhabitants, the income from deep-sea mining may in reality be limited, as royalties and tax rates will likely have to be set at a low level to incentivize mining (Cardno 2016; Mullins and Burns 2018). Furthermore, due to a lack of financial, technical and institutional capacity, the countries may undervalue the potential adverse environmental impacts associated with the exploitation of the resource, as well as any potential impacts on other economic sectors such as fishery and tourism (Christiansen et al. 2019). Moreover, asymmetric power relations, which occur when one partner is considerably stronger than the other and influences the terms of the contract in its favor, could further reduce the benefits for the host country. In the deep-sea mining context, this risk is particularly pronounced as many developing countries choose to enter into contracts with foreign mining companies and investors (Le Meur et al. 2018). This not only applies to areas within national jurisdiction but also to the Area, where several developing states act as sponsoring States for companies of their own nationality which are, however, subsidiaries of large foreign corporations. Examples include Nauru Ocean Resources Inc., Tonga Offshore Mining Limited, and Marawa Research and Exploration Ltd., who are nationals of Nauru, Tonga, and Kiribati, respectively, but subsidiaries of the Canadian Company DeepGreen Minerals Inc. (Casson et al. 2020).

If deep-sea mining is to take place, revenues generated by deep-sea mining will have to be carefully invested to ensure long-lasting benefits for the community. The development of an effective fiscal and revenue management framework prior to the commencement of mining is considered an essential pre-requisite in this regard (UNDP and UN Environment 2018). Such frameworks are recommended to include provisions on competitive procurement procedures, frequent independent audits of financial accounts, and the regular disclosure of non-commercial and non-confidential information to the public. Furthermore, transparency and the delineation of clear decision-making strategies are considered essential to minimize the risks of corruption and mismanagement of revenues (Sachs and Warner 1995; Ovesen et al. 2018).

An effective fiscal and revenue management regime can also limit the adverse impacts of asymmetric power relations (Le Meur et al. 2018). If managed poorly, the revenues obtained from mining may easily turn into a resource curse for the host countries, which has been frequently shown in the context of terrestrial mining. Particularly, developing countries which usually have less diverse economies, run the risk of becoming overly dependent on the extractive industry. In this case, countries become increasingly vulnerable to external economic shocks caused by changes in commodity prices and production levels (Ovesen et al. 2018). Furthermore, they are prone to experience the Dutch disease, which describes a situation where economic growth in one sector, i.e., the extraction of a natural resource, leads to a decline in other sectors. The increased influx of foreign currencies as a consequence of the increased export of the resource may lead to the appreciation of the local currency, which may cause other sectors of the economy to become less competitive on the international market. The Dutch disease can be prevented or counteracted by developing clear budgetary plans, detailing in advance how and when revenues are to be invested in the short-, medium- and long-term (Soros 2007; Ovesen et al. 2018). Furthermore, the establishment of offshore wealth funds in foreign currencies outside the country has been identified as a measure to ensure economic security even after the revenues from deep-sea mining decline (Al-Hassan et al. 2013). If and how the Dutch disease may affect countries involved in deep-sea mining, is yet to be researched.

Particularly developing countries often lack the capacity to develop, implement and enforce effective legislative frameworks (Bradley and Swaddling 2018). This is critical, as structural and administrative weaknesses can lead to revenue losses and negatively affect the credibility of the framework among local and foreign investors (Ovesen et al. 2018). However, several organizations exist to assist governments with the development of fiscal and revenue management regimes, such as the SPC and the Pacific Financial Technical Assistance Center (PFTAC). The latter has, for example, aided the Cook Islands' Seabed Mineral Authority in developing a mining tax regime. Previously, the Commonwealth Secretariat's Economic and Legal Section (ELS) had carried out a Seabed Minerals Fiscal Regime Analysis in 2012 and provided recommendations to the Cook Islands' government to consider in the preparation of its mining and fiscal regime to ensure consistency with international practice and stakeholder expectations. The Cook Islands' fiscal regime has recently been passed in parliament and will be administered by the Ministry of Financial Economic Management (CI Seabed Minerals Authority 2019).

5.2 The Area

In the Area, the ISA is obligated by UNCLOS and the 1994 IA to develop a payment regime composed of a payment mechanism, which determines the financial contributions contractors have to make to the ISA in exchange for exploiting the resources of the Area (CHM), and a benefit-sharing mechanism, according to which the economic and non-economic benefits of deep-sea mining will be shared among the ISA's member States (UNCLOS, Article 140) (Van Nijen et al. 2019; Jaeckel 2020; Jaeckel et al. 2016). In developing the payment regime, the ISA has to follow six principles outlined in the 1994 IA, which demand that the payment mechanism must be "fair, non-discriminatory, simple, and within the range of payments prevailing for land-based mining" and contain a procedure for monitoring compliance (Jaeckel et al. 2016: 199). The process of developing a payment mechanism is ongoing. Open question concern inter alia, the type and level of revenue raising charges to be contributed by the contractors and ways to account for the high risk of the contractors in developing the emergent industry (Van Nijen et al. 2019). ISA consultants have suggested the implementation of a 2% ad valorem royalty during the early phase, which would later be increased to about 6% as the industry grows. In this case, about 70% of the proceedings would flow to the contractors, 2%–6% would be transferred to the ISA, and the remainder would be paid as income tax to the country in which the contractor pays taxes (e.g., the sponsoring State) (The African Group 2018; Levin et al. 2020). The proposal has, however, been criticized by some of the ISA's member States, particularly by the African Group, which considers the revenue that would be raised by this scenario insufficient to compensate the ISA member States for the loss of resources in the Area (The African Group 2019; Levin et al. 2020).

Like the payment mechanism, the benefit-sharing mechanism is still being developed. However, neither UNCLOS nor the 1994 IA specifies what the benefits to mankind entail and how they should be shared. This could, for example, include the direct re-distribution of the financial contributions from the contractors or the investment of their contributions into a fund (Christiansen et al. 2019). Given the current perspective on the level of royalties set by the ISA, it seems unlikely, however, that this will generate reasonable income for developing countries (The African Group 2018; Jaeckel 2020). The sharing of benefits could also include the provision of capacity-building opportunities and the sharing of scientific research findings. To this end, the ISA has, for example, initiated several training programs and issued several scholarships. Christiansen et al. (2019: 77) point out that this could be improved through better organization and the establishment of "dedicated organs such as a school or university that systematically organizes education and capacity-building according to overarching educational goals." Furthermore, scientific data has, thus far, only been shared to a limited extent, although it has frequently been called for that particularly environmental data should be made available to the public (Seascape Consultants 2014; Jaeckel et al. 2016; ISBA/20/C/31 and ISBA/18/C/20).

6 Social considerations

The potential social impacts of deep-sea mining have, thus far, received little attention in research. Therefore, their nature and magnitude remain largely unknown. Wherever deep-sea mining takes place in the vicinity of coastlines, concerns have been raised about potential direct and indirect impacts on fisheries and tourism (Koschinsky et al. 2018; Folkersen et al. 2018a; Roche and Bice 2013; Binney and Fleming 2016). In comparison to terrestrial mining operations, which often provide indirect employment opportunities through the development of settlements around mining operations, deep-sea mining will take place with little to no presence on land. Furthermore, deep-sea mining operations require highly skilled personnel with experience in the fields of offshore engineering, project management and shipboard services. Thus, it is unlikely that many jobs will be filled by members of the local communities (Binney and Fleming 2016). Whether the inhabitants of coastal countries will benefit socially from deep-sea mining operation in their vicinity strongly depends on how their governments will choose to invest the revenues obtained from mining. If invested properly, the countries' additional income could contribute to the improvement of community and health services, infrastructure, or affordable housing. Mismanagement and corruption, however, could negate any potentially positive impacts.

Whereas governments have generally responded positively to the prospects of hosting deep-sea mining operations in areas within their jurisdiction, local communities, as well as a number of national and international NGOs have assumed a more critical position (Koschinsky et al. 2018). This became particularly apparent in relation to the struggles of Nautilus Minerals, which are attributed in part to vehement community opposition. Although it has yet to be explored how people form their opinion of deep-sea mining (e.g., based on experience with similar industries like terrestrial mining, on scientific facts or other factors), some insight has been gained from the Nautilus Minerals case in Papua New Guinea. In relation to this project, Filer and Gabriel (2018) identified three different arguments frequently voiced by opponents to the Solwara 1 project. The first one emphasized the application of the precautionary approach and, therefore, called for an interruption of all mining-related activities until sufficient knowledge on its associated environmental impacts is available. The second argument is a religious or spiritual one, which portrays the ocean as a sacred space that must not be affected by mining. The third argument is of legal nature and relates to the right of local communities of free, prior and informed consent (FPIC), as stated in the United Nations Declaration on the Rights of Indigenous

Peoples (UNDRIP). In the context of deep-sea mining, which will take place far offshore, it is, however, difficult to identify who would be entitled to FPIC (see Filer and Gabriel (2018) for a thorough assessment of this problem).

To increase the social sustainability of deep-sea mining operations, it is necessary to anticipate any potential social impacts prior to the commercialization of the activity. Important tools in this regard include social impact assessments (SIAs) (often included in EIAs) and the development of corresponding social impact management plans (SIMPs). Like their environmental counterparts, SIAs provide information about expected impacts to inform the decision-making of governments, stakeholders, and the public, while SIMPs detail suitable response mechanisms. They further describe how potential positive impacts could be enhanced (Franks 2011; Franks and Vanclay 2013). Furthermore, more consideration should be given to FPIC and stakeholder participation in general (see Singh and Hunter 2019 for an assessment of existing regulatory frameworks with respect to the incorporation of FPIC and stakeholder participation). Social impacts should, in any case, become a central component of deep-sea mining risk assessments.

7 Synthesis

7.1 Implications for sustainable development

Whether deep-sea mining can contribute to sustainability and sustainable development first and foremost depends on how sustainability is understood. In this regard, a distinction is commonly made between strong sustainability and weak sustainability. The concepts are closely linked to the five capitals theory, which assumes that there are different forms of capital: 1) natural capital (e.g., natural resources, ecosystem services), 2) financial capital (e.g., revenues), 3) manufactured capital (e.g., goods, technology), 4) human capital (e.g., work force, educational levels, skills of individuals), and social capital (e.g., norms, social networks, cooperation and trust) (Ang and van Passel 2012; Moldan et al. 2012). From a weak sustainability perspective, sustainability or sustainable development can be achieved by transforming one form of capital into another, as long as the overall stock of capital is maintained or increased. In contrast to this, proponents of the strong sustainability concept believe that the individual forms of capital need to be maintained in and of themselves. This is especially true for natural capital, which is considered vital for the growth of the other forms of capital and, therefore, essentially irreplaceable by other forms of capital.

From a strong sustainability perspective, deep-sea mining would be inacceptable, as it not only describes the exploitation of a finite resource but is also associated with substantial environmental impacts. From this perspective, the only viable option would be to reduce the demand for primary metals by increasing the rate of recycling, improving product design, and increasing the longevity of products. This would also be in line with SDG 12, which calls for more sustainable consumption and production patterns. From a weak sustainability perspective, deep-sea mining could be considered sustainable if the conversion from natural capital (i.e., the resource in the ground and the in-tact ecosystem) into the other forms of capital (e.g., revenue, goods, or employment) would keep the overall level of capital at least constant. This requires a careful weighing of the benefits and costs of deep-sea mining.

By generating additional revenue for developing states through royalties and corporate income tax, deep-sea mining could theoretically contribute to achieving economic prosperity and human well-being, as, for example, called for by SDG 1 (ending poverty), SDG 2 (ending hunger), SDG 3 (health, well-being) and SDG 10 (reduce inequality within and among countries). Here, the CHM, which specifically requires the equitable sharing of the monetary and non-monetary benefits obtained from the exploitation of the marine mineral resources in the Area, is of particular importance (see also Christiansen et al. 2019). Furthermore, deep-sea mining can provide the metals required for producing the technology needed for the transition to a low-carbon economy. Crystalline photovoltaic panels, for example, contain substantial amounts of Al, Cu, and Ag, as well as several other metals in smaller quantities. Wind turbines need significant quantities of Fe, Cu, and Al. Electric vehicles typically use lithium-ion batteries to store electricity, which requires substantial quantities of metals like Ni, Co, Al, and Mn oxides, depending on the specific type of battery. In addition to this, electric vehicles and wind turbines often operate permanent magnet generators, which require significant quantities of rare earth elements (REEs), such as Nd and Dy (Grandell et al. 2016). Many of these metals could likely eventually be extracted from marine mineral deposits. In this regard, deep-sea mining could contribute to achieving SDG 7 (sustainable and modern energy for all), specifically SDG 7.2 (“By 2030, increase substantially the share of renewable energy in the global energy mix”) and SDG 11 (“make cities and human settlements, inclusive, safe, resilient and sustainable”) if sustainable transport refers to electromobility (although this appears to be far-fetched). Following this line of reasoning, deep-sea mining could also indirectly contribute to achieving SDG 13 (“take urgent action to combat climate change and its impacts”).

However, deep-sea mining will entail the large scale and long-term destruction of the marine environment in and around the mine sites and cause inevitably the loss of biodiversity. In this regard, deep-sea mining stands in stark contrast to SDG 14 (“sustainable life under water”), specifically SDG

14.2 ("sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans"). However, the restoration of adversely affected deep-sea ecosystems is particularly difficult and expensive. Furthermore, if ecosystem services, especially the ability of the ocean and the seafloor to sequester carbon from the atmosphere, are compromised, deep-sea mining may also conflict with SDG 13 ("combating climate change"). Moreover, it is doubtful whether the revenues that could be generated by collecting royalties and income taxes (if paid to the host country), would be high enough to promote economic growth, improve social services and support institutions. Furthermore, mismanagement of revenues and the undervaluation of environmental impacts could cause the decline of other economic sectors, negatively affect the environment, and provoke social unrest. The latter may be the case particularly in developing countries which often lack the financial and institutional capacity to develop, implement and enforce sound regulatory frameworks. Figure 17 provides an overview of the various environmental, economic, and social impacts discussed in the sections above.

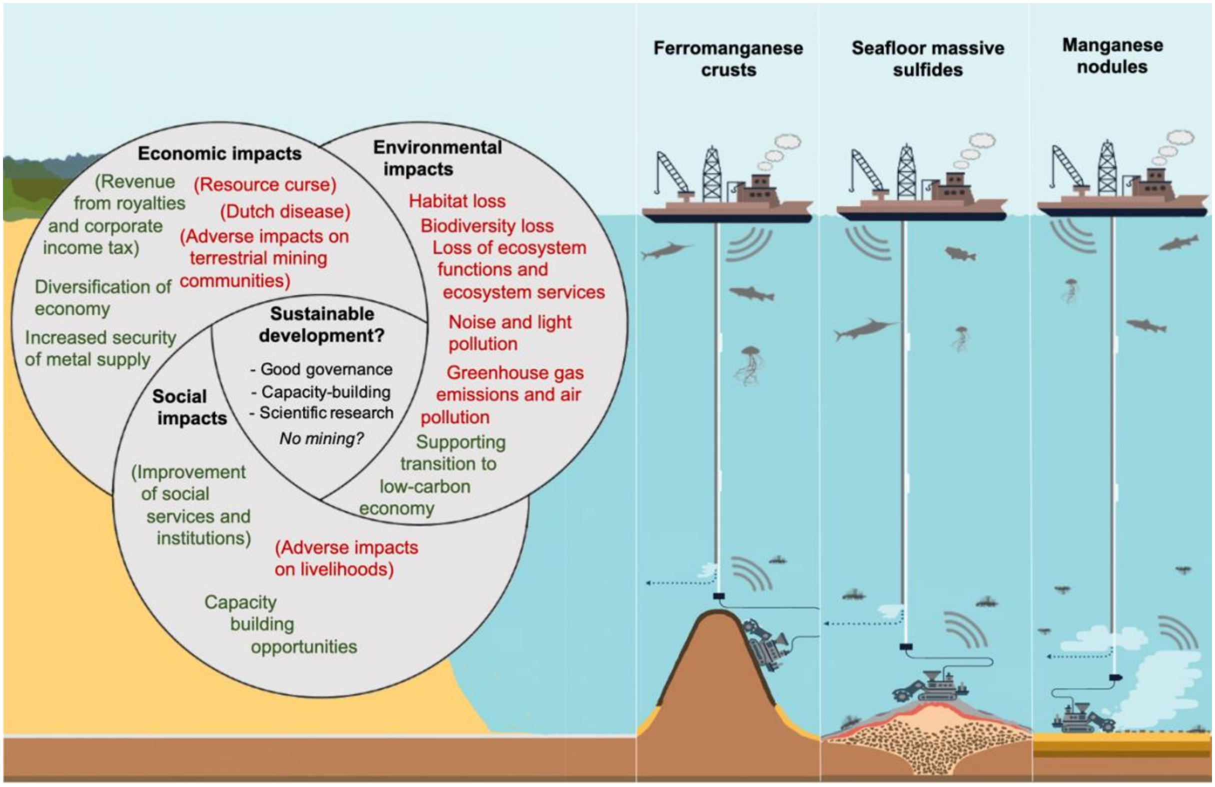

Figure 17: Overview of marine mineral deposits, mining techniques, and impacts. Positive and negative impacts are shown in green and red, respectively. Impacts in parentheses indicate potential impacts, which can be good or bad depending on external factors, such as the availability of effective policies or capacity-building initiatives. Impacts without parentheses are certain. Source: Figure by author; modeled after (Aldred 2019) (reprinted from Heinrich and Koschinsky 2021).

7.2 Good governance

If deep-sea mining cannot be prevented, it is important to reduce its adverse impacts as much as possible, for example, by implementing principles of good governance. The core characteristics of good governance include: (1) rule of law, (2) accountability, (3) strategic vision, (4) responsiveness, (5) consensus orientation, (6) equity, and (7) effectiveness and efficiency (Kardos 2012). Although different institutions emphasize different elements, there is consensus that good governance is a crucial foundation of sustainable development. Ardron et al. (2018) have analyzed the role of transparency in the context of deep-sea mining in detail, which according to them, also relates to the elements of public participation and accountability. Based on a thorough review of existing codes of conduct, regulations, international agreements, and voluntary standards, Ardron et al. (2018) identify six components of good practice in transparency and analyze to what extent the regulations and recommendations set forth by the ISA reflect these core aspects. They conclude that the ISA has been forward-thinking in some ways, for example, with respect to releasing information after a certain time and the emphasis on the precautionary approach. Furthermore, they state that the draft exploitation regulations appear to indicate that transparency may be improving to a certain extent, for example, with respect to making exploitation contracts publicly accessible (although some have criticized that the ISA's effort is still not sufficient, see above). At the same time, the ISA's rules and regulations and procedures do not seem to reflect best practices. For instance, the evaluation of the six components of transparency indicated weaknesses, such as the inaccessibility of annual reports, which are treated confidentially, unclear quality assurance, the lack of reporting on the compliance of states and contractors to ISA regulations, the lack of public participation (observers are not allowed to attend key committee meetings), and the limited possibility for civil society or State Parties to request a review or appeal to decisions of the authority.

Good governance also plays an important role, where developing countries are planning to host deep-sea mining operations in their EEZs or on their extended continental shelves. In these countries, the implementation and success of good governance principles is often limited by a lack of trained personnel capable of developing effective policy frameworks (e.g., fiscal and revenue management plans and environmental regulations), controlling the quality of impact assessments (e.g., EIAs and SIAs) and impact management plans (e.g., environmental management plans (EMPs), SIMPs), and monitoring compliance and enforcement. Capacity-building is, therefore, not only important with respect to minimizing the potential negative impacts of deep-sea mining, but also with respect to maximizing potential benefits of the activity. The Natural Resource Charter also provides guidance for "governments, societies and the international community", although their implementation may be challenging (Cust and Manley 2014: 4).

Cust and Manley (2014: 9) highlight in particular, that applying EIA methodology, albeit a well-established process, is difficult in the context of deep-sea mining, which is “a frontier industry with scant environmental data on the status quo, and with no functional precedent in terms of project design.”
In contrast to terrestrial activities, which usually benefit from information of experiences made with similar processes in similar environmental settings, there is no such option for deep-sea mining. Furthermore, there is no definition yet of what actually constitutes serious harm. Experience from terrestrial mining can, however, be used, where conflicts of ownership or between users of the marine environment occur. Kung et al. (2020: 8) add that “uncertainties are translating into defects in emergent [deep-sea mining] governance architecture”, both within and beyond the limits of national jurisdiction.

Independent of the decision for or against deep-sea mining, research on deep-sea ecosystems and potential environmental, economic and social impacts of deep-sea mining should be continued, as the past decades have shown that the interest in deep-sea mineral deposits may periodically reoccur (Sparenberg 2019), and future generations should have a solid foundation of knowledge to make decisions based on scientific facts.

Conclusion

Chapter 6: Conclusion

Since the publication of Mero's book 'The Mineral Resources of the Sea' in 1965, considerable effort went into researching the formation, composition, and abundance of marine mineral resources and the impacts associated with mining them (Mero 1965; Glasby 2002; Shirayama et al. 2017). On the one hand, the assessments confirmed the enormous resource potential of manganese nodules (Mn nodules), ferromanganese (FeMn) crusts, and seafloor massive sulfide (SMS) deposits, which for some elements even exceeds that of equivalent terrestrial reserves (Hein et al. 2013; Petersen et al. 2016). On the other hand, the assessments indicated that deep-sea mining will have severe and long-term effects, which will inevitably threaten marine ecosystems, compromise ecosystem functions, and services, and adversely affect human livelihoods (Roche and Bice 2013; Koschinsky 2016; Weaver and Billet 2019). With commercial deep-sea mining on the horizon, society urgently needs to evaluate the costs and benefits of deep-sea mining and decide whether the economic and material prospects of exploiting marine mineral resources would be worth its associated environmental, social, economic, and cultural costs.

This thesis examined the environmental, economic, social, and legal implications of deep-sea mining and identified and addressed some of the many open questions that remain even after several decades of thorough research. Moreover, it has discussed whether deep-sea mining can help achieve the UN's SDGs. Chapter 2 demonstrated that deep-sea mining is a highly complex issue, which involves multiple stakeholders with often vastly differing opinions on the necessity of deep-sea mining. It emphasized the need for interdisciplinary and integrated impact research to understand deep-sea mining impacts within individual disciplines and anticipate how impacts in one field can directly or indirectly influence impacts in another. Chapter 2 also highlighted the profound imbalance between impact assessments in different fields (Koschinsky et al. 2018). While environmental impact assessments (EIAs) have become an essential requirement in customary international law and a central aspect of the approval process of deep-sea mining exploration and exploitation contracts in the Area, social impact research has received far less attention (Pulp Mills on the River Uruguay 2010, para. 204-205; Shirayama et al. 2017; Durden et al. 2018). However, this kind of research is significant, considering that social acceptance or the lack thereof (i.e., missing 'social license to operate') can be a decisive factor in a mining project's success or failure (Mason et al. 2010; Durden et al. 2018; Filer and Gabriel 2018). Moreover, considering the growing interest of small island developing states in exploiting their mineral resources, often through foreign companies, understanding the socio-economic and socio-cultural impacts of deep-sea mining becomes increasingly relevant. Chapter 2, furthermore, indicated that many open questions remain that urgently need to be addressed to be able to holistically assess deep-sea mining impacts. These include, for example, questions related to the release of GHG emissions and atmospheric pollutants.

As chapters 3 and 4 demonstrated, the current neglect of emissions to air in deep-sea mining impact research and policymaking can in part be attributed to the lack of reliable data on the energy demand of commercial deep-sea mining operations (Heinrich et al. 2020). However, the more profound reason may be the ambiguity concerning the responsibility for dealing with the issue on an international level. Contrary to emissions released on land or within coastal waters, which are usually allocated to the countries in which they arise and expected to be mitigated by them under domestic law (via the UNFCCC and PA in the case of GHG emissions), and emissions caused by international shipping, which are addressed under MARPOL, emissions resulting from deep-sea mining currently remain unregulated. Considering that GHG emissions will eventually contribute to climate change, which already threatens the ecosystems and humans worldwide, this regulatory gap urgently needs to be closed. Based on the assessment presented in chapter 4, it is, therefore, recommended that emissions resulting from the excavation, vertical transport, and shipboard processing of marine mineral resources are integrated in the rules, regulations and procedures set forth by the ISA, which seems to be the most suitable forum to tackle the issue. A first step to do so would be for the ISA take the lead in coordinating a joint task force with the UNFCCC and IMO to clarify competencies and find effective ways to ensure the effective, cost-effective, and practical regulation of deep-sea mining-related GHG emissions.

Chapter 5 considered deep-sea mining once more from a broad perspective and assessed the activity from a sustainability angle. Whether deep-sea mining can contribute to sustainable development and help achieve the UN's SDGs is difficult to answer at this point due to numerous uncertainties concerning the development of the industry and the behavior and response of the actors involved. On the one hand, deep-sea mining is undoubtedly incompatible with SDGs 12 ('sustainable production and consumption patterns') and SDG 14 ('sustainable life below water') (Christiansen et al. 2019; Heinrich and Koschinsky 2021). In line with this, it is incompatible with the concept of 'strong sustainability,' which mainly considers the exploitation of finite resources unacceptable. From this point of view, the only possible option would be to decrease the overall demand for primary metals by, for example, strengthening the circular economy, substituting non-renewable with renewable materials, and changing overall consumer behavior. However, it is questionable whether this would suffice, considering the ever-increasing metal demand of the growing world population, the increasing demand of developing countries for economic growth and prosperity, and the widespread desire for everyone to own smartphones, computers, televisions, and other electronic devices (Watzel et al. 2020).

If deep-sea mining cannot be entirely avoided, it undoubtedly needs to be carried out in a way that maximizes its monetary and non-monetary benefits at minimal environmental and social costs. Based on the assessment presented in chapter 5, this requires strict regulation, sound environmental and social impact management plans, financial management plans, the application of the precautionary approach, and the implementation of good governance principles, including transparency. The ISA has already issued exploration regulations and environmental recommendations for deep-sea mining in the Area and is currently in the process of drafting corresponding exploitation regulations. Furthermore, the ISA is presently developing a financial mechanism as required by UNCLOS and the 1994 IA in relation to the CHM. Although there are still shortcomings due to persisting knowledge gaps regarding the type, magnitude, and timeframe of environmental impacts, this is a promising development. Nevertheless, there is room for improvement with respect to the development of regional environmental management plans (REMPs) and the determination of threshold values. In any case, the ISA should be prepared to prohibit deep-sea mining in the Area if this is in the best interest for mankind as a whole, on whose behalf the ISA is required to act.

In territorial and archipelagic waters, exclusive economic zones (EEZs), and on continental shelf areas, coastal countries enjoy sovereign rights over living and non-living resources. As such, they can decide if and under which conditions they want to pursue the exploitation of marine mineral resources within their jurisdiction. Although UNCLOS obligates these countries to implement environmental regulations that are "no less effective" than the corresponding provisions in international law, the assessment in chapter 5 showed that particularly small island developing states often lack the financial and administrative capacity to enforce this regulation. Moreover, as Singh and Hunter (2019) point out, the language in their respective regulatory frameworks is often weak and the regulations themselves do not always give sufficient relevance to the protection of the marine environment and the prior consultation of local inhabitants. Although some of these issues can likely be alleviated in cooperation with industrialized countries with greater financial and administrative capacity or NGOs, external parties will only have limited influence and their assistance will always be conditional on the invitation by the respective coastal countries.

An alternative way to influence the deep-sea mining industry both within and beyond the limits of national jurisdiction may be through the financial sector. Realizing deep-sea mining operations will require considerable capital. Reflecting society's increasing awareness of environmental and social impacts in the production of goods and services and its growing desire to make supply chains more sustainable, many banks and financial institutions have begun to place greater emphasis on evaluating their investments based on sustainability and governance-related criteria. Examples include the World

Bank, the International Finance Corporation, and other financial players. Moreover, the EU has recently issued the 'Regulation 2020/852 on the establishment of a framework to facilitate sustainable investment,' which clearly outlines the EU's intent to steer private financial investments towards projects supporting climate change mitigation and adaptation, the "sustainable use and protection of water and marine resources", the "transition to the circular economy," "pollution prevention and control," and the "protection and restoration of biodiversity and ecosystems" (Article 9).

Another frequently asked question is whether deep-sea mining would be better or worse than terrestrial mining, although it has been argued that this question may be entirely unwarranted, considering that deep-sea mining would most likely not replace terrestrial mining but be carried out in addition to it (Christiansen et al. 2019). In a direct comparison of terrestrial and deep-sea mining, there may be good reason to give preference to the exploitation of marine mineral resources. Firstly, there is no need for deforestation, the removal and storage of overburden or the relocation of local inhabitants. Secondly, there is no incentive for child labor and no need for immobile infrastructure. However, contrary to terrestrial mining, the impacts of deep-sea mining will be very long-lasting, if not permanent. Moreover, deep-sea mining operations will likely not provide any employment opportunities for the local communities and any economic and social benefits for local inhabitants will likely depend on how the governments choose to spend and invest the income from deep-sea mining. In addition to this, it is not clear yet if and how deep-sea mining in coastal zones will affect other economic sectors like fisheries and tourism. Furthermore, after closure of the mines, terrestrial mine sites can often be restored or repurposed, whereas restoration and recultivation of deep-sea mines is considerably more costly (if at all possible).

Nevertheless, as long as there is no final decision in favor or against deep-sea mining on the international and national level, it is important to continue researching the impacts of deep-sea mining (taken for itself, and in comparison, with terrestrial mining) to further improve the understanding of the activity's direct and indirect consequences. In this regard, research should also focus on alternative paths such as the improvement of terrestrial mining practices and ways to reduce society's overall demand for primary metals.

Scientific work

Chapter 7: Scientific work

1 Scientific work related to this thesis

1.1 Published and unpublished articles included in this thesis

Koschinsky A, **Heinrich L,** Boehnke K, Cohrs JC, Markus T, Shani M, Singh P, Smith Stegen K, Werner W. 2018. Deep-sea mining: Interdisciplinary research on potential environmental, legal, economic, and societal implications. Integrated Environmental Assessment and Management. 14(6):672–691. doi:10.1002/ieam.4071.

Heinrich L, Koschinsky A, Markus T, Singh P. 2020. Quantifying the fuel consumption, greenhouse gas emissions and air pollution of a potential commercial manganese nodule mining operation. Marine Policy. 114:103678. doi: https://doi.org/10.1016/j.marpol.2019.103678.

Heinrich L, Koschinsky A. 2021. Deep-sea mining: Can it contribute to sustainable development? In: Hornidge A-K, Ekau W, editors. Transitioning to sustainable life below water. Basel (CH): MDPI.

Heinrich, L., Markus T., Singh, P., Smith Stegen, K. Regulation of GHG emissions resulting from deep-sea mining in the Area (unpublished draft)

1.2 Published articles, policy briefs, and workshop reports not included in this dissertation

Heinrich, L., Lehnen, F. Petersen, S. 2018. Final Workshop Blue Mining: Breakthrough Solutions for Sustainable Deep-Sea Mining, Aachen, October 2017 (commissioned by German Marine Research Consortium, KDM).

Heinrich, L. 2016. Deep Sea Mining – What next for Science? Briefing Report. Brussels (BE), (commissioned by German Marine Research Consortium, KDM).

Heinrich L. 2020. Tiefseebergbau: Ein Umweltproblem? Hydrographische Nachrichten. 117:56–63. doi:10.23784/HN117-09.

1.3 Research projects

Heinrich L. 2020. Comparison of energy and material flows associated with the metallurgical treatment of terrestrial nickel laterite deposits and deep-sea manganese nodules. (German: Vergleich der Energie- und Materialflüsse bei der metallurgischen Aufbereitung von Manganknollen und landgebundenen Nickellaterit-Lagerstätten. Commissioned by Federal Institute for Geosciences and Natural Resources, BGR).

1.4 Conference presentations

Heinrich, L. and Koschinsky, A. 2018. "Deep-Sea Mining Impacts above the Surface – Quantifying the Fuel Consumption and Associated Air Pollution of a Commercial Mn Nodule Mining Operation in the CCZ." In 48th Underwater Mining Conference, Bergen, Norway (Talk)

Heinrich, L. and Koschinsky, A. 2017. Assessing the sustainability of manganese nodule mining: a life-cycle based comparison of commercial mining scenarios in the German license areas in the CCZ. 46th Underwater Mining Conference (UMC), Berlin, Germany (Talk).

1.5 Research proposals

"Deep-sea mining: Risk assessment from a transdisciplinary perspective" submitted to Belmont Forum. 2018.

1.6 Co-supervised bachelor thesis and guided research projects

Dawood, M. 2018. A multi-criteria comparative analysis of deep-sea mining for copper with land-based mining. Bachelor Thesis. Jacobs University Bremen.

2 Scientific work unrelated to this thesis

2.1 Research cruises

M 147 – GEOTRACES (April – May 2018)

Five-week research cruise with RV METEOR (M147, Amazon GEOTRACES) in the Amazon estuary, equatorial western Atlantic.

2.2 Research proposals

"Emerging Critical Metal Contaminants (ECMCs) at the land-ocean continuum along the North Sea coast - monitoring and mitigation of anthropogenic impacts" submitted to The German Marine Research Alliance, DAM. 2020.

2.3 Co-supervised bachelor thesis and guided research projects

Opatz,C. 2017. Sustainable Tourism and its development potential for Small Island States – A case study of the Seychelles Islands. Bachelor Thesis. Jacobs University Bremen.

2.4 Teaching

Transatlantic Summer Academy on Sustainability (Jacobs University, InterCultur), 2017.
Anthropogenic Impacts on the Earth's Surface Environment, 2019. Teaching assistant.
Current Topics in Resource and Environmental Sciences, 2021. Teaching assistant.
Environmental Geochemistry, 2018. Teaching Assistant.
Fieldtrip Environmental Changes and Challenges in Northwestern Germany, 2017, 2018, 2019. Teaching assistant.
Foundations of Earth and Environmental Sciences, 2019. Teaching assistant.
IEA Seminar II, 2016. Teaching assistant.
IES Seminar III, 2016, 2017. Teaching assistant.
International Energy and Environmental Politics, 2016. Teaching assistant.
Off-shore Wind Energy (Intersession), 2017. Teaching assistant.
Water: Introduction to the most precious substance of the 21st century, 2016. Teaching assistant.

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Acknowledgements

Acknowledgements

First of all, I would like to extend my sincere thanks to my supervisor, Andrea Koschinsky, who introduced me to the field of environmental studies and interdisciplinary research during my bachelor studies and who welcomed me back in her work group as a PhD student a few years later. I am grateful for her continuous support, for integrating me into her professional network, and for always finding ways to prolong my work contract at Jacobs University. Thank you also for letting me join the research cruise M147, which was a genuinely great experience. I also wish to thank, Karen Smith Stegen, whose lectures on geopolitics have sparked my interest in the topic. You have taught me a lot about academic writing, especially in the field of policy, which helped me tremendously with my dissertation. Thank you for your continuous support and trust.

I am also grateful to Till Markus, who has taught me a lot about international environmental law and policy. Thank you for believing in me (and my choice of topics) and being patient when my way of thinking was closer to that of a natural scientist than a lawyer. Many thanks also to Hermann Kudrass, who helped me particularly in the early phase of my Ph.D. Thank you for sharing your knowledge and experience with the technical side of deep-sea mining operations, and for giving me your author copy of the Sharma (2017) book. It has been very helpful to have a hard copy of the book at hand.

Special thanks go to Pradeep Singh, a fellow Ph.D. student and co-author of many of my articles, who has helped me tremendously throughout my entire Ph.D. Without your insight in marine governance, international environmental policy and law, and the ‘inner workings’ of the ISA, it would have been much more difficult for me to turn my ideas into publishable articles.

I also wish to thank Marcus Ihms (DNV), who has taught me how to calculate the fuel consumption of ships of different sizes that are moving at different speeds. Without your assistance, it would have been considerably more challenging to complete my article on the emissions to air released by deep-sea mining. Similarly, I would like to thank Simon Boel (GSR). Moreover, I would like to express my gratitude to all my co-authors.

I would, furthermore, like to acknowledge the financial support I obtained during my Ph.D. studies. Thank you to Jacobs University for supporting my Ph.D. studies with a three-year stipend. I also appreciate the support from GLOMAR, which has offered interesting courses and funding to attend a short course at the University College London and the Underwater Mining Conference in Berlin. Lastly, I am grateful for the DAAD's financial support, which allowed me to attend the Underwater Mining Conference in Bergen.

I would also like to express my appreciation to my colleagues at Jacobs University. Thank you for all the great discussions, Christmas and graduation parties, summer BBQs and after-work outings to the Freimarkt and the Christmas markets. My special thanks go to Kathy and Sophie, who I have become close friends with already during my undergraduate studies. Knowing that they would be on my side during the Ph.D., as well, has made my decision to come back to Jacobs University easy.

Last but not least, I would like to thank my friends and family for their support. Special thanks go to my parents who have always had my back.