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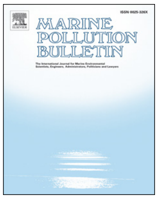

Review

Assessing the impacts of seabed mineral extraction in the deep sea and coastal marine environments: Current methods and recommendations for environmental risk assessment

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ABSTRACT

Mineral extraction from the seabed has experienced a recent surge of interest from both the mining industry and marine scientists. While improved methods of geological investigation have enabled the mapping of new seafloor mineral reserves, the ecological impacts of mining in both the deep sea and the shallow seabed are poorly known. This paper presents a synthesis of the empirical evidence from experimental seabed mining and parallel industries to infer the effects of seabed mineral extraction on marine ecosystems, focusing on polymetallic nodules and ferromanganese concretions. We use a problem-structuring framework to evaluate causal relationships between pressures caused by nodule extraction and the associated changes in marine ecosystems. To ensure that the rationale behind impact assessments is clear, we propose that future impact assessments use pressure-specific expert elicitation. We further discuss integrating ecosystem services in the impact assessments and the implications of current methods for environmental risk assessments.

1. Introduction

The accelerating progress of new technologies is increasing the demand for raw materials (Vidal et al., 2017). The scarcity, declined grades, and conservation of terrestrial natural resources are attracting growing interest in the extraction of minerals from the seabed (Jenkins and Joppa, 2009; Calvo et al., 2016). As a result of rising metal prices and technological advances in mining, offshore mining activities are now being outlined in the deep sea (Hein et al., 2013; Beaulieu et al., 2017). Although a range of mining operations have been active in shallow sea areas for decades, the technological challenges and the high cost of exploration in the high seas are further driving interest in mineral extraction from shelf seas (Hannington et al., 2017). While the improved methods of geological investigation have enabled high resolution mapping of new seafloor mineral reserves, the ecological impacts and large-scale consequences of seabed mining in both coastal seas and the deep sea are still poorly known.

Environmental impact assessment (EIA, Munn, 1979; Glasson et al., 2013) is a key tool in planning and evaluating the effects of human activities on the environment. The obligation to conduct an EIA is determined by a number of international legislative treaties and customs that specify the structure and scale of the assessment (Pérez, 2017). In principle, an EIA is required for activities that are considered to have a significant adverse impact on the environment. In marine areas within national jurisdiction, EIAs are required depending on the country's legislation, both in the territorial waters and Exclusive Economic Zones (EEZs) to indicate what types of activity may be allowed and where. As a result of the increased economic interest in the high seas, EIAs and increased protection measures are called for areas beyond national jurisdiction (Druel, 2013). While a number of international legal and policy instruments require projects to undergo EIAs in international waters, effective enforcement and supervision for such obligations and the content of assessments is lacking (Ma et al., 2016). Similarly, in areas within national jurisdiction, the EIA regulations for the marine environment are often less comprehensive than those for terrestrial activities, and many countries do not require offshore activities to undergo an EIA (Guerra et al., 2015).

To support the ecological component of EIAs in identifying the potential impacts of an activity on specific ecosystems, ecological impact assessments (Treweek, 2009) are increasingly included in the EIA process. Unlike EIAs, the implementation of an ecological impact assessment is not a statutory requirement, and can be used for projects of

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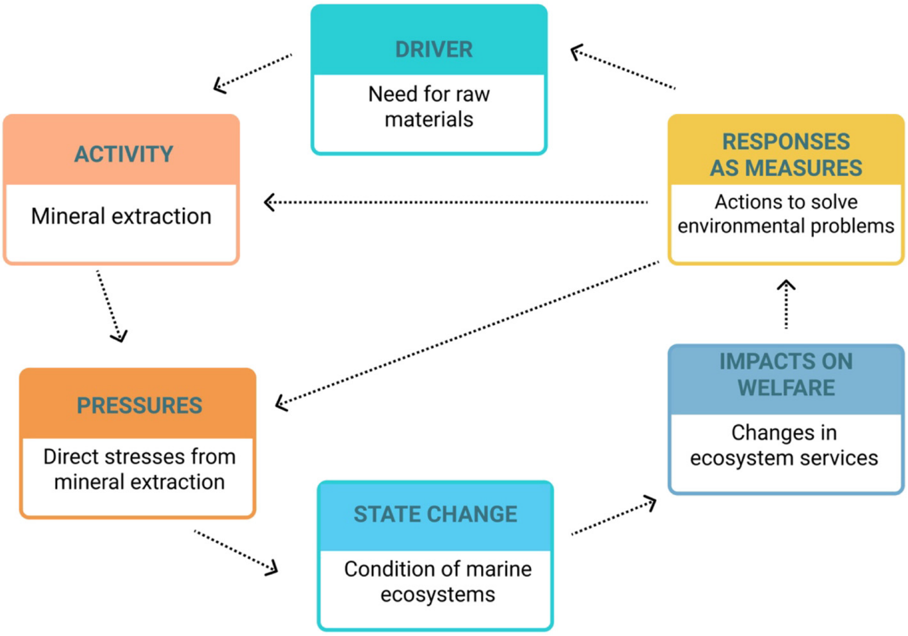

Fig. 1. The DAPSI(W)R(M) framework applied to seabed mineral extraction. The arrows denote causal interactions within the components of the framework. Adapted from Elliott et al. (2017).

any scale. Traditionally, ecological impact assessments have built on knowledge of how ecosystems respond to human-induced disturbances. The risks of adverse effects on ecosystems caused by human activities are assessed based on the prevailing condition of the environment against which the presumed impacts are compared (Therivel, 2012; Glasson et al., 2013). However, in the case of seabed mineral extraction, little previous experience from mining projects has been documented. Moreover, the scarcity of biological and geological baseline data on the deep and shallow seabed is another major issue in evaluating the impacts of physical disturbance (Gjerde, 2006; Wright and Heyman, 2008), and the justification for statements on the severity of the impacts is not always well detailed (Thompson et al., 1997; Drayson et al., 2015).

The findings of ecological and environmental impact assessments are summarized in environmental statements, which should include accurate information on the magnitude and severity of the potential risks of the activity to support decision making (Treweek, 2009). To ensure the transparency of impact statements, more structured approaches for estimating the adverse effects on marine ecosystems are required compared to traditional EIAs. Here, we utilize the Drivers-Activities-Pressure-State changes-Impacts(on Welfare)-Response(as Measures) framework (DAPSI(W)R(M) (Elliott et al., 2017) to evaluate the requirements for ecological impact assessments of seabed mineral extraction in a generalized context. We examine the impacts of marine mineral concretion mining with the aim of improving future quantitative estimations of impacts by comparisons with similar activities and pressures. Moreover, we discuss the critical knowledge gaps and prerequisites for environmental risk assessment for seabed mineral extraction. The focus of this review is on the impacts of mining two types of marine mineral precipitates: deep-sea polymetallic nodules and shallow-water ferromanganese concretions. We will refer to the mining of both mineral concretion types in the review as “mineral extraction”.

Research on the ecological impacts of marine mineral extraction has mostly focused on aggregate extraction (e.g. Newell et al., 1998, 2004) and anthropogenic activities in the deep sea (Newell et al., 1998; Ramirez-Llodra et al., 2011). In coastal seas, the environmental impacts of dredging have been investigated for decades as a result of the intense use of marine aggregates (e.g. De Groot, 1979; Newell et al., 1998; Desprez, 2000; Cooper et al., 2007a,b; Waye-Barker et al., 2015). Regardless of recent concern over the impacts of seabed mining (Boschen et al., 2013; Miller et al., 2018), current knowledge of the pressures from seabed exploitation on ecosystems has not been synthesized, and studies addressing the adverse effects rarely offer empirical evidence of the overall impacts. Rather, previous reviews on the impacts of marine mining have focused on the loss of biodiversity and recovery of benthic fauna (Ellis, 2001; Jones et al., 2017) or on specific ecosystems, such as hydrothermal vents (Boschen et al., 2013; Van Dover, 2014) or polymetallic nodule fields (Vanreusel et al., 2016). While different scenarios of the potential impacts have been envisaged (Van Dover, 2010; Ramirez-Llodra et al., 2011), links between the findings of empirical studies and specific pressures from mining have not been established. The current challenges regarding mineral extraction from the seafloor are how to estimate the impacts on ecosystems before commercial activities start and how to deal with uncertainty stemming from the scarcity of data.

To adequately allocate research and management efforts, it is essential to point out the knowledge gaps in our current understanding of the impacts of marine mineral extraction. Here, we review the empirical evidence concerning the impacts of anthropogenic seabed disturbance on marine ecosystems and evaluate the methods used to assess the impacts. We identify the impacts that have been thus far been examined in in situ experiments or by modeling, and have gathered information on the effects that have been left unaddressed, but are crucial to a comprehensive risk assessment of seabed mining activities. In this review, marine mineral extraction is considered as an activity that causes multiple pressures on different ecosystem and habitat components, resulting in a variety of changes in the state of the ecosystem (Fig. 1). We focus on addressing the causal relationships between the direct stressors from mineral extraction and the observed changes in the environment using the DAPSI(W)R(M) - framework. As commercial nodule and concretion mining activities have not yet started, this provides a unique opportunity to integrate losses to ecosystem services into the risk assessment and environmental management of seabed mining.

2. Application of the framework

We define the impacts associated with seabed mineral extraction using the DAPSI(W)R(M) framework to facilitate more comprehensive impact assessments and monitoring of the impacts (Fig. 1). It is an extension of the Drivers-Pressures-State-Impact-Response (DPSIR) framework widely used in environmental management to assess the links between the causes and responses to change (Atkins et al., 2011). The DAPSI(W)R(M) approach recognizes that the drivers fuel activities that lead to the pressures. Uncontrolled pressures lead to state changes in the natural system, which may be positive or negative, and further have an impact on the human system (Elliott, 2014). Here, the impacts are defined as consequences for human welfare to avoid confusion with the impacts on the environment, which are described as State changes in the framework (P. Cooper, 2013).

The advantage of a structured approach is in presenting key causal relationships in a concise way. Using a problem-structuring linkage framework enables a systematic presentation of the available information to assess causal relationships between human activities and changes in the ecosystem and the reduction of impacts on the marine environment (Knights et al., 2013). A systematic approach to ecological impact assessments is required if quantitative estimates of the impacts are to be made.

2.1. *Driver: need for raw materials*

Accelerating urbanization and the intensive use of metals in electronics and high technology have increased the demand for both aggregates and rare earth elements (Vidal et al., 2017). Seabed resources of commercial interest for mining include polymetallic nodules and ferromanganese concretions, cobalt-rich ferromanganese crusts, metalliferous muds, and seafloor massive sulfides (Rona, 2008; Peukert et al., 2018). Polymetallic nodules are mineral concretions largely composed of manganese and iron oxides and oxyhydroxides, forming at the sediment-water interface in soft sediment abyssal plains with low sedimentation rates at water depths of approximately 3000 to 6500 m (Schulz and Zabel, 2006; Hein et al., 2013). Nodules form around a solid nucleus by hydrogenetic precipitation from the seawater and diagenetic accumulation from the metals dissolved in the sediment pore water (Cronan, 1980; Peukert et al., 2018). The growth rates of deep-sea nodules are on average 1–6 mm Ma^{-1}, with measured values of up to 250 mm Ma^{-1} (Hein and Koschinsky, 2014; van Stackelberg, 2017). In shallow marine environments, ferromanganese concretions form around a nucleus at rates 3–10 times greater than deep-sea nodules (Grigoriev et al., 2013; Zhamoida et al., 2017) and display a different mineralogy and chemical composition (Schulz and Zabel, 2006). Both deep-sea and shallow water concretions sustain a diverse and abundant microbial community (Blöthe et al., 2015) and their formation is partly catalyzed by micro-organisms, e.g. archaea and bacteria (Zhang et al., 2002; Yli-Hemminki et al., 2014). Depending on their formation, nodules can contain substantial concentrations of economically interesting metals, such as cobalt, copper, and nickel, along with valuable rare earth metals, such as lithium and titanium (Hein et al., 2013).

Nodules in the depths of the ocean have recently gained attention due to their substantial resource potential and environmental issues related to their exploitation (Vanreusel et al., 2016). Regardless of the interest in deep-sea nodules, seabed metal precipitates are also found in various shallow sea areas from the Atlantic (Cronan, 1975; González et al., 2010) to the Kara Sea (Baturin, 2011), the Barents Sea (Ingri, 1985), and the Baltic Sea (Winterhalter, 1980; Ingri and Pontér, 1987; Glasby et al., 1997). However, there is currently little accurate information on the distribution and abundance of the nodules (Petersen et al., 2016). Recently, the search for nodules has been narrowed to potential areas determined by the geological setting and sedimentation rates (Hein et al., 2013).

2.2. *Activity: mineral extraction*

Due to the increasing demand for clastic resources for coastal development and construction, many marine sand and gravel deposits are already subject to mining activities in shelf seas (Rona, 2008). Moreover, diamonds, gold, and tin have been mined for decades in shallow marine environments (Rona, 2008; Peukert et al., 2018). The primary global areas of economic interest for extracting nodules are concentrated within four primary zones: the Clarion Clipperton Fracture Zone in the north-central Pacific Ocean, the Peru Basin in the south-east Pacific, the Penrhyn Basin in the south-central Pacific, and the northern Indian Ocean (Petersen et al., 2016; Miller et al., 2018). The depth profiles of these areas are between 4000 and 6500 m. Nodule extraction has not been initiated commercially, nor have there been comprehensive syntheses of the environmental impacts of previous offshore mining initiatives. However, several deep-sea mining simulations and experimental mining initiatives have been undertaken since the 1970s (e.g. Thiel et al., 2001). The experiments have usually consisted of disturbing the seafloor or collecting nodules for relatively short periods of time, ranging from hours to days. A more detailed overview of simulated disturbance studies in the deep sea is given in a meta-analysis by Jones et al. (2017). Mineral extraction initiatives for metal concretions in shallow sea areas have been less studied. In 2006–2008, the first experimental-industrial ferromanganese concretion extraction using a dredge pump took place in the Eastern Baltic Sea at depths of 25–28.5 m (Zhamoida et al., 2017).

As mining systems have not been operated commercially, the physical effects of nodule mining must be inferred from the structure of the currently available machinery and technology. Shallow water concretion extraction would likely be done by suction hopper dredging, but the specific configuration for deep-sea nodule extraction remains more uncertain. While there is no clear consensus on the best technique, hydraulic dredging combined to a nodule collector is currently recognized as the most feasible extraction method (Jones et al., 2017). A planned mining system for polymetallic nodules would probably consist of a remotely operated nodule collector, a mining support vessel, a riser and lifting system, and a waste-water re-circulation system connected to the mining platform for the discharge of sediment, discharge water, and erode nodule material (Thiel and Tiefsee-Umweltschutz, 2001; Peukert et al., 2018). A description of some of the most recent plans for nodule mining activities in the deep sea and more technical details are given, for example, in Volkmann and Lehnen (2017).

Several options remain for the best available practice for nodule extraction with a combination of these different configurations. In the most basic case, nodules and the semi-liquid layer of the sediment collected from the seafloor are lifted on board a mining support vessel by a hydraulic transport pump system. The ore-containing slurry is dewatered and the residual sediment is pumped back to the sea. To minimize the dispersion of sediment plumes, the slurry may be discharged close to the ocean floor (Volkmann and Lehnen, 2017). To further avoid tailings dispersal, another currently considered technique is to separate sediment and nodules on the seafloor without pumping the sediment to the surface. In this case, nodules would be extracted by a collector that sieves the upper layers of the sediment, separating nodules from the sediment and redepositing it on the seafloor. Nodules may then be pumped up to a mining support vessel to be dewatered, the remaining water then being returned to the sea (Weaver et al., 2018). In certain designs, the system would not include a riser for pumping nodules to the mining support vessel. While other collector types may cause different types of specific disturbance to the seafloor, similar configurations and pressures on the environment may be expected. The extraction techniques for deep and shallow seabed are schematically illustrated in Fig. 2.

As metal concretions are collected from the sediment surface, nodule and concretion mining may essentially be considered as a dredging operation, with similarities to aggregate extraction. As a difference to aggregate extraction, metal concretions are found on soft bottom sediments and the affected habitat is thus a combination of soft and hard substrates. In shallow-water mining, where the mixing layer covers a larger portion of the water column, the effects of sediment dispersal are

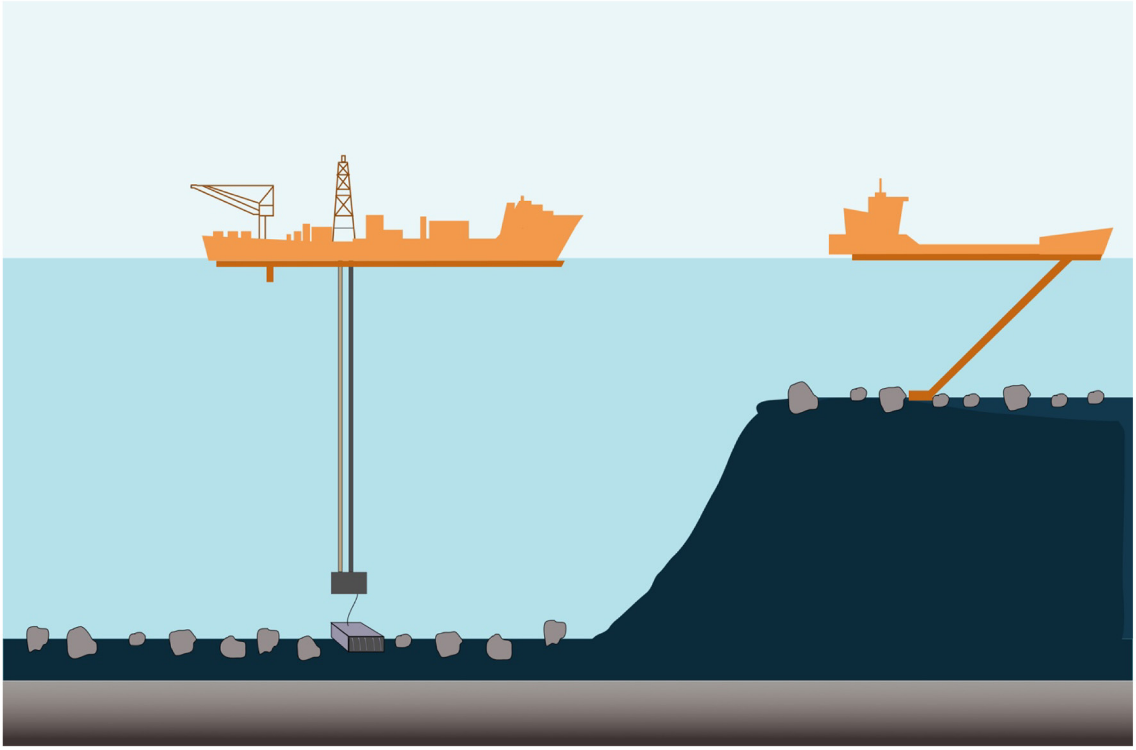

Fig. 2. Schematic illustration of polymetallic nodule extraction by a mining device (left) and ferromanganese concretion extraction by suction dredging (right). In deep-sea polymetallic nodule extraction, the nodules are collected by a mining device and pumped or lifted up to a mining support vessel. The nodules may be separated from the sediment at the seafloor or on board the operational vessel. Shallow water ferromanganese concretions can be extracted by a suction hopper dredger. Figure not to scale.

less likely to be avoided. While the chemical composition and processes of geological formation differ between deep sea and shallow water mineral deposits, a similar methodology for estimating the ecological impacts may be applied.

2.3. Pressure: direct stresses from mineral extraction

Pressures can be described as the mechanisms causing an effect in any part of the ecosystem possibly altering the state of the environment (Oesterwind et al., 2016). Within the DAPSI(W)R(M) framework, the physical and chemical forces associated with the activity or drivers of change are considered as pressures caused by mineral extraction activities, which result in state changes in multiple biological and physicochemical ecosystem components (Fig. 3).

Mechanical stress due to the removal of seafloor substrate is the most direct pressure from mineral extraction. The time scales of mineral concretion formation range from hundreds to thousands of years for ferromanganese concretions, to millions of years for deep-sea nodules (Schulz and Zabel, 2006). While reformation does occur on longer time scales and concretions are considering geologically as transient features on the seafloor, on a biological scale, we consider the removal of concretions as a permanent modification of the seabed morphology. To correctly quantify the damage to the marine environment and the ecological footprint, information on the duration of the disturbance, the area affected, and the amount of removed mineral material is required.

Extraction of mineral material causes sediment plumes both near the seafloor and in the water column. Near-bottom plumes are created by the physical disturbance of the sediment by a mining device (Oebius et al., 2001; Glover and Smith, 2003), when the surficial sediment is resuspended. Nodule-harvesting removes the top layer of the sediment, spreading suspended solids into the water column (Oebius et al., 2001; Thiel and Tiefsee-Umweltschutz, 2001). The other potential source of plumes is the material transported to the mining platform at the ocean surface, where the extracted material may be separated from water and sediment and transferred to a transport vessel (Amos and Roels, 1977). In aggregate extraction a similar process, screening, is performed to separate the desired sediment fraction from the rest of the extracted material by releasing the excess fraction at the surface, causing more diffuse effects over a larger area. If nodules will be separated from the sediment at the seafloor, the plume will be a result of the discharge water released from pumping the nodules up into the mining support vessel. Sediment dispersion changes both the chemical properties of the water and the seafloor sediment composition (Newell et al., 1999; Desprez et al., 2009). The resulting plumes may increase the concentrations of suspended particles for tens to hundreds of km from the extraction site (Rolinski et al., 2001).

Considerable quantities of organic contaminants and heavy metals may be released from the seabed sediments when they are disturbed (Latimer et al., 1999). The finest particle fraction stays in the water column the longest and will thus be transported the furthest. This fraction is the one potentially containing the highest concentrations of harmful substances due to its sorptive nature (Grimwood and McGhee, 1979). In addition to the metals and contaminants potentially present in sediments, sediment disturbance will also release naturally occurring components from the anoxic layers. Hydrogen sulfide (H_2S), formed in the dissimilatory reduction of sulfate by anaerobic bacterial respiration, is abundant in sediments in coastal areas with a high organic matter content (Libes, 2011). The release of sulfides during sediment disturbance is a well-known concern within dredging activities due to their toxicity to many organisms (Evans, 1967; Wang and Chapman, 1999), and it must therefore be taken into consideration for mineral extraction activities in shallow areas. While considerable research efforts have been put into estimating the release of harmful substances from sediments, the fate and bioavailability of contaminants from disturbed sediments is not well understood (Eggleton and Thomas, 2004, Roberts, 2012). Consequently, few studies have identified harmful substances as

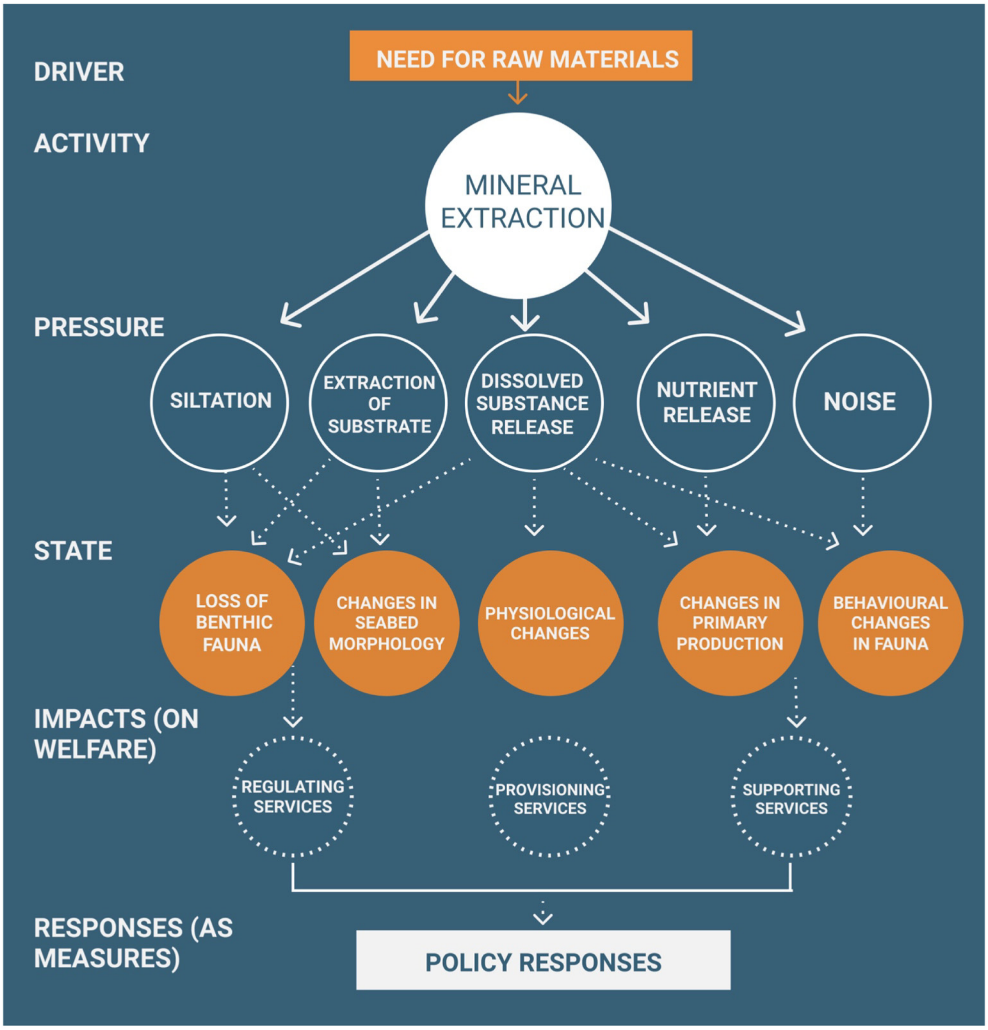

Fig. 3. Pressures and impacts of seabed mineral extraction within the DAPSI(W)R(M) framework in form of a simplified causal network. A more comprehensive description of the links between components of the framework is given in Table 1.

a stressor when monitoring the impacts of dredging operations (Roberts, 2012). During in situ experiments with large undisturbed sediment cores, stirring of the upper centimeters of sediment immediately released dissolved pore-water constituents such as heavy metals and nutrients (Koschinsky et al., 2001). Surface sediment plumes may thus substantially increase turbidity and inorganic nutrient concentrations in the water column. Although nodules and concretions may be extracted intact without crushing them on the seafloor, certain mineral precipitates are very fragile and easily break apart during extraction. As the hard mineral substrate may be transformed into smaller particles during extraction, metals may be released to the water column in dissolved and particulate phases (Hauton et al., 2017).

Mineral extraction by hydraulic dredging emits noise, although few estimates have been published to date (Robinson et al., 2011). Underwater noise is produced by operating the dredge, the physical disturbance of the seafloor and shipping operations (McKenna et al., 2012). Dredging vessels are estimated to produce a noise output comparable to a loud cargo vessel (Robinson et al., 2011) and the produced noise is concentrated at low frequencies (< 1 kHz) (Thomsen et al., 2009). Regardless of the similar machinery, nodule harvesting may produce more intense levels of underwater noise due to differences in the grain size of the extracted material. However, with a limited number of studies undertaken, the impacts of noise remain uncertain and it is not possible to extrapolate the potential effects from these studies to different areas with variable environmental conditions.

While mineral extraction causes immediate damage to the extraction area, the range of impacts may extend to hundreds of kilometers from the mining site depending on the scale of the extraction activities (Oebius et al., 2001). Dispersal is dependent on the stratification of the water column and the depth of the surface mixing layer. Sharp pycnoclines reduce vertical mixing and promote the horizontal dispersion of suspended particulate matter (Ellis, 2001). The spatial extent of the impacts is substantially smaller if no screening is performed (Hitchcock and Bell, 2004), depending, however, on the current regime of the extraction area. Numerical models are commonly used to determine the transport and fate of the sediment plume and suspended compounds from mineral extraction (Jankowski et al., 1996; Sharma et al., 2001). The models describe particle suspension, deposition, settling rates, aggregation, and flocculation based on empirical- and physics-based equations (Sharma, 2005; Smith and Friedrichs, 2011). However, uncertainties remain especially for estimating the fate of deep-sea plumes due to scarcity of in-situ observations and the limited knowledge on the characteristics of suspended material and rates of suspension (Aleynik et al., 2017). Results from modeling using estimated particle-size distributions suggest a wider distribution of sediments than those observed in in situ studies (Jankowski et al., 1996; Oebius et al., 2001). Critical reviews of the methods for assessing sediment plume dispersal further suggest that the methods currently used to estimate sediment dispersal from dredging are not based on the most recent data and models (Spearman, 2015). Consequently, the estimated ranges of impact for the biological effects of aggregate extraction are also potentially erroneous. Sediment plumes have critical importance in impact assessment, as they may extend the impacts of nodule harvesting far beyond the limits of the extraction site. The indirect impacts of sediment deposition on neighboring sites can be as significant as the direct impacts due to substrate removal (Desprez, 2000). Adequate estimation of the sediment dispersal area is thus a key issue in estimating the impacts of seabed mineral extraction.

2.4. State changes: condition of marine ecosystems

The responses of an ecosystem to pressures from mineral extraction are reflected by state changes in the DAPSI(W)R(M) framework. In the context of ecological impact assessment, a state change reflects the response of the ecosystem to changing environmental conditions. Pressures are the mechanism of change, leading to both physicochemical and ecological state changes. To adequately estimate the state changes, there is a need to define the footprint of the effect, to quantify the ecosystem damage, and to estimate how long it will take for the community to recover, if recovery is possible given the changes in the environment. The state changes resulting from mineral extraction vary from local short term changes related to the removal of fauna and behavioral and sublethal changes associated with underwater noise to the long-term ecosystem effects of changes in the community related to habitat changes (Kenny and Rees, 1994; Newell et al., 1998). A schematic summary of the environmental stressors and associated ecosystem responses resulting from seabed mineral extraction is given in the form of a causal network in Fig. 3.

Habitat loss is the most direct result of extracting material from the seafloor. When aggregates or metal concretions are removed from the seafloor, the seafloor geomorphology is often permanently modified, as the hard substrate is lost. The removal of nodules eliminates the hard substrate, reducing the heterogeneity of the seabed. Mineral extraction activities that cause topographical changes on the seabed may modify its biogeochemical processes. Large pits and borrow holes created when using a suction dredger in shallow areas may trap organic matter, enriching the sediment and increasing the oxygen consumption as the organic matter decomposes (Graca et al., 2004). Excessive organic matter accumulation may eventually lead to anoxic conditions and toxic hydrogen sulfide formation (Libes, 2011). Furthermore, the extraction of material from the seabed changes the composition of the sediments. In the Eastern Baltic Sea, ferromanganese nodules collected from an experimental extraction site had a different geochemical composition compared to nodules collected from a reference area, indicating the dissolution of the nodules buried in the anoxic sediment by extraction activities (Zhamoida et al., 2017).

In situ experiments on the recovery of disturbed seabed habitats are a common way of quantifying the impacts of mining activities (Jones et al., 2017). The ecological impact studies published to date have mostly focused on either aggregate extraction in shallow sea areas or examining the physical and ecological effects of the deep-sea disturbance (Table 1). Most studies have investigated impact and reference sites (e.g. Desprez, 2000; Waye-Barker et al., 2015), whereas in certain studies, a potential impact area has also been included (Desprez, 2000; Cooper et al., 2007a). While a number of before-after-control-impact paired-series (BACI-PS) studies on the impacts of aggregate extraction have been performed at the same site (Kenny and Rees, 1996; Van Dalfsen et al., 2000), it is unclear whether the applied biological indices adequately address recovery, as univariate indices may address recovery quicker than multivariate ones, as seen in (Bolam and Whomersley, 2005; Froján et al., 2011).

The direct removal of fauna through sediment extraction of the sediment is the immediate consequence of physical pressures in the marine environment. The majority of studies have concentrated on the benthic infauna due to their limited mobility, thus being useful in defining the spatial range of changes in the ecosystems with respect to the extraction site (Newell et al., 2004; Boyd et al., 2005; Cooper et al., 2007a,b; Waye-Barker et al., 2015; Jones et al., 2017). It is noteworthy that the ecological consequences of seabed mineral extraction are not limited to the direct removal of benthic organisms, but also include habitat loss and the modification of seabed morphology, physiological disturbance to organisms, and changes in the intra- and interspecific competition patterns affecting food web structures (Table 1). For decades, research on the ecological impacts of seabed mining has focused on addressing the biological community structure using univariate indices such as abundance, the number of species, and biomass (Table 1). The use of univariate measures is, however, not trivial as the identity of species occurring in the community remains uncertain and changes in community composition are not apparent in these measures, although the changes may have significant implications for other species and ecosystem functions (Thistle, 1981; Warwick and Clarke, 1991; Tillin et al., 2006). Multimetric indices expressing diversity and accounting for species sensitivity may better demonstrate disturbance effects (Diaz et al., 2004). However, species sensitivity should be evaluated in a case-specific manner, as it may vary depending on the pressure and prevailing environmental regime (Schiele et al., 2016). Further, Biological Traits Analyses (BTA, Bremner et al., 2003; Bremner, 2008) can describe the functional properties of the community and detect potential changes linked to ecosystem services provided by the macrofaunal community.

Sediment plumes in the water column and near the seafloor may result in multiple changes in the marine environment. Even low levels of sediment redeposition may be destructive to certain benthic organisms as increased solids in the water may smother or clog their feeding organs or gills (Ellis et al., 2002), especially harming filter-feeding organisms such as mussels and other bivalves (Mestre et al., 2017). Suspended solids and increased sedimentation as a result of harvesting the sediment may cause significant reduction in light availability (Kirk, 1977), leading to the reduced vitality or death of aquatic macrophytes (Riul et al., 2008). Increased nutrient concentrations in the water column due to sediment resuspension (Klump and Martens, 1981; Lohrer and Wetz, 2003) may result in phytoplankton blooms. In oligotrophic waters, the intrusion of nutrient rich bottom water and sediment may drastically increase primary production (Hyun et al., 1998).

The release of metals and harmful substances from the sediment and through the weathering of solid mineral material may exert sublethal effects on both benthic and pelagic organisms (Simpson and Spadaro, 2016). In solid phases metals are not bioavailable and toxic, but metal complexes are reversible, and changes in environmental conditions may alter metal partitioning and bioavailability (Calmano et al., 1993; Cantwell et al., 2002). Aquatic organisms may be exposed to harmful substances via the ingestion of contaminated particles, passive diffusion, or active transport through membranes. Uptake rates are highly dependent on the age, behavior, ecology and previous exposure of the individual, varying within and between species (Luoma, 1983; Luoma and Rainbow, 2005). Different taxa thus vary in their tolerance of increased metal concentrations (Rainbow, 2007), and the sub-lethal effects of chronic exposure should be included in the state changes, in addition to the acute effects (Hauton et al., 2017). However, with limited information on the physiology of deep-sea organisms, it is currently not possible to estimate the toxic impacts from metal release from the mined material on deep-sea species (Hauton et al., 2017).

In the literature, the impacts of mineral extraction on mobile species are considered less significant than the damage to sessile benthic fauna, as they may avoid the impact area and external disturbances (De Robertis and Handegard, 2013). Fish and other fauna can, however, be affected by the indirect effects of reduced food sources and habitat modification. Changes in sediment grain size and loss of the original substrate can reduce optimal spawning and nursery grounds for certain fish species (Foden et al., 2009), particularly demersal egg-laying teleosts (de Groot, 1980, Kaiser et al., 1999). The increased levels of

Table 1

Pressures and associated state changes resulting from seabed mineral extraction with examples of ecosystem indicators, and affected underwater ecosystem services from deep and shallow seabed.

Pressure	State change	Indicators	Affected ecosystem services	References
Extraction of seafloor substrate	Loss of benthic fauna by direct removal	Macrofaunal abundance and diversity	Biodiversity, secondary production, trophic support, existence value	(Miljutin et al., 2011), (Borowski, 2001), (Newell et al., 2004), (Kenny and Rees, 1994, 1996)
	Habitat loss and degradation	Suitable habitat abundance	Habitat provision, existence value	(Vanreusel et al., 2016), (Khripounoff et al., 2006)
	Loss of fauna attached to nodules	Megabenthic fauna	Biodiversity, existence value, trophic support	(Bluhm, 2001), (Vanreusel et al., 2016)
	Changes sediment composition	Fish diversity, Incomplete recovery of fauna	Biodiversity, existence value, trophic support	(Hwang et al., 2013), (Desprez, 2000), (Van Dalfsen et al., 2000), (Waye-Barker et al., 2015), (Robinson et al., 2005)
Siltation and resuspension of sediment	Smothering of fauna	Macrofaunal recovery	Biodiversity, trophic support	(Hussin et al., 2012), (Desprez et al., 2009), (Cooper et al., 2007b), (Desprez, 2000), (Boyd and Rees, 2003)
	Smothering of benthic flora	Recovery of benthic flora	Biodiversity, trophic support, biomaterials for industrial and pharmaceutical uses	(Lyngby and Mortensen, 1996, McMahon et al., 2011, Onuf, 1994, Riul et al., 2008)
	Behavioral changes in animals		Biodiversity, fish catch	(Hecht, 1992)
	Changes in sediment composition	Sediment grain size and biochemical composition	Habitat provision, nutrient cycling	(Cooper et al., 2011, Le Bot et al., 2010)
	Incomplete recovery of fauna	Macrofauna, sediment composition	Nutrient cycling	(Desprez, 2000), (Van Dalfsen et al., 2000), (Waye-Barker et al., 2015), (Robinson et al., 2005)
	Changes in seabed geomorphology	Sediment composition	Nutrient cycling	(Le Bot et al., 2010, Uścinowicz et al., 2014), (Khripounoff et al., 2006)
	Loss of fish nursery grounds	Sediment composition, fish abundance	Biodiversity, fish catch	(Scharf et al., 2006)
Release of substances from the sediment	Sublethal effects on fauna	Feeding and reproduction of fauna, increased concentration of contaminants and their bioavailability after dredging	Biodiversity, fish catch	(Roberts, 2012, Simpson and Spadaro, 2016) (Bradshaw et al., 2012)
	Nutrient release from the sediment	Chl *a*, *Synechococcus* cell number, inorganic nutrient concentration	Chemosynthesis, Photosynthesis, aesthetic value	(Hyun et al., 1998, Lohrer and Wetz, 2003)
	Increased turbidity	Water clarity	Photosynthesis, aesthetic value	(Sharma et al., 2001)
Underwater noise	Disturbance to animals	Feeding and resting of animals	Fish catch, existence value	(Roberts et al., 2015, Robinson et al., 2011)
Underwater light	Disturbance to animals	Feeding and resting of animals	Fish catch, existence value	(McFarland, 1986)

suspended particulate matter and toxic substances from the sediment plume can potentially harm the eggs and larvae (Auld and Schubel, 1978; Partridge and Michael, 2010). Changes in benthic species composition and an increase in opportunistic species resulting from mineral extraction can also benefit certain demersal fish as food becomes more abundant (de Jong et al., 2014). However, the adverse effects on fish have not been thoroughly addressed in the literature (Newell et al., 1998; Desprez, 2000; Stelzenmüller et al., 2010). The estimation of the changes in the abundance of fish eggs and larvae is often overlooked, as traditional sampling methods are limited to shallow depths. These limitations make the detection of changes in the abundance of mobile species challenging, in addition to the naturally variable spatial range of these organisms.

While the ecological impacts of noise produced by seabed exploitation have been left unaddressed, increased noise levels will potentially induce stress in marine organisms (Wright et al., 2007; Nichols et al., 2015; Roberts et al., 2015; Roberts and Elliott, 2017) and may cause them to avoid the extraction area. Behavioral changes in organisms may also be brought about also by increased turbidity, e.g. through changes in the foraging patterns of visual predators (Abrahams and Kattenfeld, 1997; De Robertis et al., 2003).

State changes in the environment are significant if the changes are long lasting or permanent. After external disturbance, marine communities and ecosystems may react to the pressure or their state may remain virtually unchanged. Disturbed communities may completely recover to their initial state, recover only partially, or remain in the disturbed state (Lotze et al., 2011). In cases where the external disturbance implies habitat modification, recovery to the initial state may not be possible. Polymetallic nodules provide a hard substrate on otherwise soft sediment bottoms (Veillette et al., 2007), and their removal may potentially permanently modify the seafloor community and the endemic fauna associated with them (Miljutin et al., 2011; Vanreusel et al., 2016). The long-term consequences stemming from habitat loss and the combination of multiple pressures may thus be significant, but challenging to estimate. While experimental data from comprehensive ecological studies are scarce, the poorly known food web structures combined with the impacts of cumulative pressures induce even greater uncertainty when estimating long-term changes in ecosystem functioning (Boyd et al., 2003).

The magnitude of seabed disturbance to benthic macrofauna is typically assessed through the recovery of the community to the pre-existing state (Borja et al., 2010). However, no standard definition of recovery has been established, stemming from the natural variability in marine ecosystems and populations and the different methods for defining the reference conditions (Lotze et al., 2011; Duarte et al., 2015). In most benthic disturbance studies, recovery has been assessed by measuring the recovery of species number and abundance, omitting possible alterations in community composition. The original community structure may not be able to recover due to habitat loss as a result of substrate alteration (Desprez, 2000). Communities in post-disturbance areas can differ from the original state in community composition or diversity but may still develop similar functional traits. Few detailed accounts of recovery after mineral extraction have been documented, as no exact data on the community prior to the extraction activity are typically available. With no experience of commercial mining, recovery is currently inferred from disturbance experiments, although the scale of the ecological response may not be accurate compared to commercial mining activities (Jones et al., 2017). Methods to estimate the recovery potential of species and communities from trait-based estimates of life cycles and seafloor connectivity before commercial activities start are thus required. To estimate the severity of seabed damage, levels of acceptable change must equally be set (K.M. Cooper, 2013; Levin et al., 2016).

The recovery of seabed communities is dependent on both the arrival of mobile species and successful recolonization by larvae, which in itself is dependent on neighboring habitats and connectivity (Thrush et al., 2008). Communities in naturally high-energy areas with exposure to currents or waves are more adept at readjusting to the impacts of mineral extraction than more stable communities. In the absence of primary production, the resource limited deep-sea communities have a lower abundance and are reliant on the phytodetrital nutrient supply from the surface (Smith et al., 2008). Consequently, the recovery of disturbed habitats in deep-sea environments is expected to require considerably more time than recovery in shallow-water environments, ranging from years to even decades (Thiel, 1992). In dynamic soft bottom environments, where the frequent disturbance of sediment prevents the establishment of sessile and long lived species, recovery rates of 6 to 8 months are common (Newell et al., 1998). In the shallow and brackish Baltic Sea, the recovery of the diversity and biomass of the benthic organisms in shallow waters may take up to five years (Bonsdorff, 1983).

2.5. Impacts on welfare: changes in ecosystem services

Marine areas support high biological productivity and supply some of the most important needs of humankind (Barbier, 2012; Halpern et al., 2008). Marine ecosystems produce several goods and services, such as wild biotic stocks, and potential new biological and genetic resources supported by a variety of ecosystem services (Armstrong et al., 2012; Barbier, 2017). These provisioning services are maintained by regulatory services that support many essential functions for the health of marine ecosystems. These services include, but are not limited to, food provisioning for organisms, nutrient cycling, and carbon sequestration (Armstrong et al., 2012; Barbier, 2017; Le et al., 2017). Therefore, the human welfare relies on the delivery of societal goods and benefits, which result from applying human capital and complementary assets (e.g. energy, money, time, or skills) to the ecosystem services (Elliott et al., 2017). Furthermore, marine habitats have educational and scientific value as they can be structurally complex and taxonomically diverse (Barbier, 2017). Thus, not all impacts on ecosystems will be directly detectable in the outputs and products obtained from the marine environment, and natural systems can have ecosystem services of their own and not linked to produced goods.

The utilization of ecosystem services can cause trade-offs when the provision of one service is reduced as a consequence of the increased use of another (Bennett et al., 2009; Rodríguez et al., 2006). Unintentional trade-offs occur when decision-makers are ignorant of the interactions among ecosystem services or have incomplete knowledge of their functioning (Tilman et al., 2001; Walker et al., 2002). Ecosystem services trade-offs can be irreversible when the extraction of seabed resources destroys the habitats available for biodiversity maintenance, e.g. fish nursery grounds (Rodríguez et al., 2006). Identification of the possible trade-offs allows decision-makers to better understand the long-term effects of only focusing on one ecosystem service or preferring one service over another (Rodríguez et al., 2006). Understanding of the relationships among ecosystem services is thus essential for estimating the consequences of changes in one ecosystem service through linkages to other services. However, for other than provisioning services, such as fish stocks and climate regulation, sufficient knowledge to assess the impacts of extraction and restoration is lacking. In environmental risk assessments, the estimated effects of human actions, such as aggregate extraction on ecosystem services provided by the seabed, can be based on expert opinion and the literature (Cooper et al., 2013).

The widespread state changes in the marine environment following mineral extraction may result in modifications in the functioning of marine ecosystems through the affected ecosystem components. The modifications in ecosystem functioning are perceived within the DAPSI(W)R(M) framework as changes in the state of an ecosystem and then in ecosystem services. Further, the socio-ecological framework integrates the human and social capital with delivering goods and benefits as impacts on welfare. However, the characterization of benthic ecosystem services is incomplete, largely due to scattered data on seabed characteristics (Galparsoro et al., 2014). Without knowledge of the functioning of marine ecosystems associated with mineral deposits, changes in the state of an ecosystem after modification of the environment cannot be estimated. Identifying the services provided by seabed ecosystems is therefore essential for estimating the impacts of mining. Regulatory services are challenging to estimate by definition, and are often approached by the valuation of marine ecosystems with a range of methods to value biodiversity (Laurila-Pant et al., 2015).

A key issue in the management of seabed exploitation is examining how ecosystem structure and ecological functions convert into benefits to society. The changes in the state of ecosystem components may be recoverable or reversible, determining the degree of impacts on ecosystems. Adequately estimating the potential state changes is thus essential for translating the impacts of seabed exploitation into losses to the ecosystem services. When extraction activities are prone to causing ecologically defined irreversible harm through species extinction or habitat destruction and the existence of ecosystem services in the future is threatened, the valuing of ecosystem services is highly relevant. However, a major challenge in this valuation is to quantify the marine ecosystem services in a comprehensive manner.

2.6. Responses as measures: governance of seabed mineral resources and risks

Assessing the relationships between pressures and impacts is essential to the effective long-term management of seabed ecosystems subject to exploitation. Regardless of the changes in the state of the environment, the modifications in ecosystem services will ultimately drive management actions. Well-estimated state changes enable the quantification of potential effects on ecosystem services and enhance informed decisions concerning where to target management measures.

The governance of seabed exploitation is essentially about minimizing the interaction between the state changes and impacts on welfare with policy and management measures (Fig. 3) through economic and legal instruments, ecological compensation actions, technological advances, and responding to societal needs and values. The responses may be targeted at different stages of the assessment, to expected and potential risks from the activity or to observed state changes and impacts (Fig. 1). These measures include regulating the intensity of exploitation, with the lack of exploitation as an alternative (Levin et al., 2016), site selection for mineral extraction (Boschen et al., 2013), the creation of reserves protected from mining (International Seabed Authority, 2011), and stakeholder consultation for socially sustainable mining practices.

To respond to monitoring needs following human activities, there has been a need to define a healthy ecosystem and to develop methods to assess it (Halpern et al., 2012). This implies characterizing which factors constitute a healthy ecosystem, and linking these to what may be expected in an ecosystem under non-disturbed conditions (Tett et al., 2013). It is important to carefully choose the indicators for assessing ecosystem change under pressure so that the variables present a comprehensive view of the ecosystem, without being excessive (Tett et al., 2013). However, as yet there has been no clear consensus regarding what constitutes effective protection and serious harm to the marine environment in relation to seabed mineral extraction and the ecosystems associated with marine mineral deposits (Levin et al., 2016). The challenge in this case primarily stems from the limited of knowledge of the ecosystems associated with nodules and concretions. For management decisions, it is essential to determine which state changes could exceed ecological thresholds and affect ecosystem functioning and services, therefore requiring management, monitoring, and possibly restraints on mining activities. Similar approaches to define a healthy ecosystem status are needed for seabed exploitation, including appropriate indicators for habitat connectivity and seabed integrity.

The environmental regulations concerning seabed exploitation differ between the seabed within and beyond national jurisdiction, as defined in the 1982 United Nations Convention on the Law of the Sea (UNCLOS, 1982). The requirement to monitor harmful effects of activities is defined under Article 206 of the UNCLOS and obliges States to assess the impacts of activities under their jurisdiction that may result in "significant and harmful changes to the marine environment and communicate reports of the results of such assessments" (Part XII Article 206). For seabed beyond national jurisdiction, the exploration and exploitation of mineral resources is governed by the International Seabed Authority, established by the UNCLOS. The ISA both grants exploration permits and regulates mining activities. While the ISA requires an EIA for seabed mineral extraction in areas beyond national jurisdiction, the existing regulations only constitute an incremental part of a comprehensive EIA. Furthermore, the current legal regime only describes a general obligation to undertake an EIA (Ma et al., 2016). It does not specify legally-binding requirements and is lacking in global mechanisms for compliance, enforcement, and supervision (Druel, 2013).

Despite the obligation to assess impacts, no general coordination or monitoring mechanism exist for the conduct of EIA. This has lead to concern over the lack of specifications concerning the content of EIAs (Durden et al., 2018). The ISA has prepared recommendations regarding baseline data collection and the management of seabed mining (International Seabed Authority, 2013). Specific guidelines for environmental impact assessment are is still under development for polymetallic nodules and cobalt-rich ferromanganese crusts, regarding the exploitation of both the international seabed and within the EEZ of UNCLOS states (International Seabed Authority, 2016a). For human activities within internal waters, territorial seas, Exclusive Economic Zones, and the continental shelf, the environmental impact assessments are conducted under each country's own regulations (UNCLOS, 1982). However, the impacts of seabed mineral extraction may reach another country's Exclusive Economic Zone or international waters through, for instance, the dispersal of the sediment plume, in which case the EIA procedure follows the Espoo convention on transboundary impacts (UNECE, 1991) and should be taken into consideration when examining the requirements for an EIA.

Economic and societal aspects play a fundamental role in environmental management, and the actions taken to reduce the adverse impacts relate to managing human behavior rather than the environment (Barnard and Elliott, 2015). For effective environmental management, the human responses to anthropogenic changes must be socially, economically, and ecologically viable and accepted (Barnard and Elliott, 2015). The measures taken to respond to the potential adverse impacts may equally target the activities within the DAPSI(W)R(M) framework. These are reflected by recent work on the technological advances to minimize the state change following seabed mineral extraction. Recently, there have been several initiatives to develop methods to minimize the environmental impacts of nodule mining (e.g. EU Horizon 2020 funded MIDAS, JPI Oceans MiningImpact, and Blue Nodules).

The successful implementation of ecosystem-based management is based on understanding the relationships between activities and the pressures they cause. Marine spatial planning is one of the management instruments used to govern the use of marine space (Douvere, 2008). Spatial planning requires knowledge of the physical and biological characteristics of the environment, as well as the relationships between the pressures and the changes in the state of marine ecosystems. For mining activities that are to cause significant harm to the environment, ecological compensation through protected areas, for example, may be considered as a mitigation measure. However, the criteria to estimate similarities between the ecosystem services lost and gained through compensation measures in the marine environment and to monitor the benefits are considered insufficient, compromising the effectiveness of these measures (Levrel et al., 2012). Furthermore, the aim of no net loss of biodiversity does not appear feasible in the context of deep-seabed mining (Niner et al., 2018), and the requirements for shallower seabed areas remain to be defined. Responses to the potential impacts of seabed mineral extraction equally include considering the need for seabed exploitation and its economic profitability in terms of the lost ecosystem services. While metals will be needed to respond to the growing population of emerging economies and green technologies (Hein et al., 2013) and the potential to increase resource efficiency and recycling to minimize the extraction of raw materials. Although recycled metal flows will only meet a modest proportion of the demand for many years to come (Reck and Graedel, 2012), there are possibilities to look into new ways to use materials, as the rare earth elements targeted by seabed mineral extraction are currently recycled very inefficiently (Graedel et al., 2011).

3. Implications for a comprehensive risk assessment

In this review, we have recognized challenges resulting from the current state of knowledge for constructing ecological impact assessments on the extraction of polymetallic nodules and ferromanganese concretions. Impact assessments are often implemented for the overall impacts of the activity, with little explanation of the rationale behind the conclusions. We argue that ecological impact assessments on the expected impacts should be done through specific pressures and the associated state changes in the ecosystem using a causal approach. When the potential impacts are addressed through causal chains, the impacts may be followed to several levels of effects through sequences of interactions between different ecosystem components. In this way, the severity of impacts may be presented in a more concise and transparent way. While the impact estimates in ecological impact assessments are based on the concept of causes and effects, the use of causal networks in EIAs has not been well adopted (Perdicoúlis and Glasson, 2012, 2006). With the cause–effect chains well illustrated throughout the impact statement process, further analyses of the risks associated with the activity may be implemented.

Environmental risks denote the combination of potential adverse effects on natural systems, species, and ecosystem processes (Burgman, 2005). Environmental risk assessment (ERA) takes into account the different plausible scenarios following human activities, evaluates the probability of the different outcomes, and the magnitude of these impacts while considering the uncertainty involved (Cormier et al., 2013). Moving from an impact assessment to a risk assessment involves adding a probabilistic element, the likelihood of a pressure having an effect (Burgman, 2005). A risk assessment framework typically consists of identifying the specific pressures and affected ecosystem components, analysing the probabilities of the impacts and evaluating the impacts under different management measures (Cormier et al., 2013). The aim of an ERA is to provide information on the optimal management decisions under uncertainty, making it a valuable tool in data-poor situations (Gentile and Harwell, 1998; Burgman, 2005).

Currently the paucity of experimental evidence and data from marine mineral extraction limits the implementation of traditional environmental impact assessments. Industrial development may, however, push management decisions to be made based on incomplete data. ERAs can play a significant role in dealing with uncertainty as a part of the ecological impact assessment. Including probabilities into the analysis both reveals and helps communicate the scarcity of data. Moreover, the implementation of a risk assessment improves the identification of all significant hazards requiring assessment considering the potential worst-case scenarios. Integrating probabilistic risk analyses into ecological impact assessment to estimate the likelihood of adverse impacts would strengthen the transparency of impact statements (Stelzenmüller et al., 2010a,b). Bayesian networks, as applied, for example, by Stelzenmüller et al. (2010a), allow the use economic and social information (Barton et al., 2008, 2012; Haapasaari et al., 2013) in addition to ecological knowledge in order to identify the balance between these three criteria of sustainability. Graphical problem-structuring frameworks, such as DAPSI(W)R(M), may be used as visual communication tools to inform risk assessment and risk management. Addressing the consequences of mineral extraction through causal networks thus lays a basis for including uncertainty and risks into the assessment. Using causal impact networks for a graphical model-based risk analysis also facilitates expert elicitation for further risk assessment procedures (Fenton and Neil, 2012; Lehikoinen, 2014). While interdisciplinary risk governance can easily become complex (Aven and Renn, 2010), it is needed in order to support science-based decision making in the various uses of marine space.

Optimal environmental management frameworks regarding the risks of seabed mining have recently been proposed by Collins et al. (2013) and Durden et al. (2018) for the deep-sea and Ellis et al. (2017) for a multitude of offshore mining activities in the continental shelf. In this review, we point out the ecosystem components that should be addressed while estimating the impacts of mineral extraction and what kind of prior evidence should be used in the impact assessment process for polymetallic nodule mining (Fig. 2). We show that the ecological impacts of seabed mineral extraction may be illustrated through main pressures, which include substrate removal, bottom and surface sediment plumes, and underwater pollution. These pressures result in a series of observable state changes in the marine environment, both on the seafloor and in the water column. It is therefore essential that impact assessments address the changes in multiple ecosystem components. While estimating the extent of pressures on marine ecosystems, cumulative and in-combination effects do not only stem from several separate activities (Borja et al., 2017), but also need to be assessed within the multiple pressures caused by a single activity (Tamis et al., 2016).

However, this literature review reveals that the ecological effects of mineral extraction are most often investigated in terms of damage to benthic organisms. Extraction of minerals from the seabed causes biological damage by directly removing benthic animals through sediment extraction, through modifications to the physical conditions of the environment, sediment deposition, habitat destruction, changes in sediment geomorphology, underwater noise, as well as through changes in water chemistry resulting from the release of nutrients, harmful substances and increased turbidity. Despite the multitude of affected ecosystem components, our results imply that the impacts of mineral extraction on the pelagic environment have largely been left unaddressed. The mismatch in research effort between the seabed habitats and state changes in the water column compromise the reliable estimation of the overall impacts. Poor characterization of the pelagic realm is a result of technological challenges due to high temporal and special variability in the biological and physicochemical characteristics of the water column (Angel, 1993; Hardman-Mountford et al., 2008). The current focus on the more sedentary seafloor ecosystems may give a simplified image of the state changes from mineral extraction. Furthermore, the coupling of benthic and pelagic habitats is important, as it supports crucial functions from nutrient cycling to energy transfer in food webs between these habitats (Griffiths et al., 2017). While marine ecosystem structures and functions are extensively affected by human actions, there are gaps in our understanding of the responses between benthic habitat and water column (Griffiths et al., 2017). To maintain the contribution of benthic-pelagic systems to ecosystem services, the linkage should be understood and included in the assessment frameworks.

The scarcity of experimental evidence and survey data on both deep-sea and shelf-sea processes calls for the use of expert judgment in impact analyses on seabed mineral extraction. Using a structured assessment framework, expert views on weakly observed variables can be estimated in a more precise manner by elicitation processes (O'Hagan et al., 2006; James et al., 2010; O'Hagan, 2012). The uncertainty regarding available data stems from both bias in research effort towards particular ecosystem components, and the natural uncertainty associated with certain ecosystem processes. These latent variables are ones that are challenging to observe due to poor detection or random variation in their occurrence. They include implications for the food web, effects on mobile species, and changes in the water column, which are by nature challenging to assess with quantitative measures, and have thus not been well addressed in the literature. In the context of impact assessments, ecosystem processes with high natural variation decrease the detection of signs of state changes caused by the pressures from human activities (Elliott and Quintino, 2007). This is especially highlighted in detecting changes in the water column and plankton systems, where the amount of natural variation produces a low signal-to-noise ratio (e.g. deYoung et al., 2004).

Effective management and conservation of marine ecosystems requires adoption of common guidelines for the content of ecological impact assessments within EIAs that acknowledge uncertainty related to the scarcity of data. While comprehensive guidelines for EIA mining in areas beyond national jurisdiction are still under development and the existing ones simply divide impacts into physico-chemical and biological effects (International Seabed Authority, 2012), the latest drafts equally recommend the inclusion of an Environmental Risk Assessment (International Seabed Authority, 2016b). However, the proposed impact assessment structure follows the traditional approach where the impacts to the environment are thought to stem from the activity with overlap in the assessment. The approach presented in this review is thus compatible with the envisioned guidelines, providing further insight into the causal relationships of seabed exploitation and changes in marine ecosystems. Regulations for ecological impact assessment for marine mineral extraction could be improved upon by describing the specific pressures, as presented in this review, and by integrating a probabilistic approach to better acknowledge the risks associated with mining activities.

4. Concluding remarks

A major issue for risk analysis of the mining of polymetallic nodules and ferromanganese concretions is the scarcity of information on their ecological and geochemical role (Vanreusel et al., 2016; Zhamoida et al., 2017). The lack of knowledge on the impacts of habitat loss, and its consequences for trophic interactions and ecosystem services limits the prediction of the ecological consequences of nodule removal. Further, without this information, the recovery of or impacts on associated organisms cannot be sufficiently estimated prior to disturbance. If appropriate scientific knowledge is lacking, even thoroughly executed impact assessments cannot succeed in describing the possible scenarios. More studies with statistically robust sampling and comprehensive experimental designs are needed to establish causalities between the pressures from mineral extraction and implications for ecosystem functioning related to the nodule habitats.

Integrating ecosystem services into the impact assessment further enables comparison of the profits from the extraction activity and the loss of ecosystem societal benefits. Ecosystem valuation can be applied to demonstrate the changes in intermediate ecosystem services, habitat abundance, or in management practices (Armstrong et al., 2012). The key gaps in valuation evidence include the lack of understanding of how the ecosystem functions are provided, the key threats to them, and how they are linked to other ecosystems, goods, and services (Armstrong et al., 2012). Although the valuation of marine ecosystem services might be uncertain, there is no reason why the future use or option values should not be considered. Constructing quantitative impact assessments through causal and probabilistic frameworks including the effects on human well-being would improve the comprehensive and transparent estimation of the overall impacts of seabed mining.

In this review, we have identified causal relationships between pressures caused by polymetallic nodule extraction and the associated changes in marine ecosystems from empirical evidence using the Drivers-Activities-Pressures-State changes-Impacts(on Welfare)-Responses(as Measures)-framework. To ensure that the rationale behind impact statements is clear and easy to communicate to stakeholders, we propose that future ecological impact assessments should use pressure-specific elicitation of expert knowledge based on the causal relationships between the activity and the ecosystem responses. Expanding the assessment to include ecological risks and their likelihoods would further improve the integrity of the impact statements. In the face of accelerating commercial interest in polymetallic nodule extraction from deep-sea and coastal seas, statements on the ecological impacts of seabed mineral extraction will need to be made. This not only holds true for polymetallic nodule extraction, but may be applied to other human activities suffering from a lack of evidence on the impacts.

Sustainable management of the marine environment is dependent on exploring how ecosystem structure and ecological functions convert into benefits to society. Data on species and habitat characteristics associated with seafloor mineral deposits are severely lacking, compromising the consistency of impact statements. Comprehensive baseline data on the biological communities and geological features of polymetallic nodule fields would facilitate mapping of the associated ecosystem services. Inferring the ecosystem functions and services associated with mineral deposit habitats is essential for estimating the impacts of mineral extraction and should be integrated into the environmental impact statements to illustrate the consequences of mining for management purposes. Estimating the potential impacts of specific pressures would enable adequate management measures or appropriate compensation decisions taken to be taken before the large scale activities begin.

Conflict of interest

Declarations of interest: none.

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