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Incorporating ecosystem services into environmental management of deep-seabed mining

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ABSTRACT

Accelerated exploration of minerals in the deep sea over the past decade has raised the likelihood that commercial mining of the deep seabed will commence in the near future. Environmental concerns create a growing urgency for development of environmental regulations under commercial exploitation. Here, we consider an ecosystem services approach to the environmental policy and management of deep-sea mineral resources. Ecosystem services link the environment and human well-being, and can help improve sustainability and stewardship of the deep sea by providing a quantitative basis for decision-making. This paper briefly reviews ecosystem services provided by habitats targeted for deep-seabed mining (hydrothermal vents, seamounts, nodule provinces, and phosphate-rich margins), and presents practical steps to incorporate ecosystem services into deep-seabed mining regulation. The linkages and translation between ecosystem structure, ecological function (including supporting services), and ecosystem services are highlighted as generating human benefits. We consider criteria for identifying which ecosystem services are vulnerable to potential mining impacts, the role of ecological functions in providing ecosystem services, development of ecosystem service indicators, valuation of ecosystem services, and implementation of ecosystem services concepts. The first three steps put ecosystem services into a deep-seabed mining context; the last two steps help to incorporate ecosystem services into a management and decision-making framework. Phases of environmental planning discussed in the context of ecosystem services include conducting strategic environmental assessments, collecting baseline data, monitoring, establishing marine protected areas, assessing cumulative impacts, identifying thresholds and triggers, and creating an environmental damage compensation regime. We also identify knowledge gaps that need to be addressed in order to operationalize ecosystem services concepts in deep-seabed mining regulation and propose potential tools to fill them.

1. Introduction

The deep sea contains many highly heterogeneous ecosystems that host a vast, but not yet fully quantified wealth of biological, energy, and mineral resources (Ramirez-Llodra et al., 2010; Mengerink et al., 2014). Benefits from these natural resources include food, fuel, raw materials, and non-market benefits (Thurber et al., 2014). As industries begin to use deep-sea resources in order to meet growing demand for food, pharmaceuticals, energy, and minerals, how these benefits are produced and maintained grows increasingly important to understand. However, many knowledge gaps still exist regarding how ecosystem structure and ecological functions translate into benefits to society. Parsing through these relationships is essential to the long-term, sustainable, and effective environmental policy and management of deep-sea ecosystems subject to exploitation.

For much of the past century, deep-sea research has focused on biological community structure by defining abundance, distribution, and diversity (Rex and Etter, 2010). More recently, there has been a shift in emphasis towards how structure, biodiversity in particular, supports ecological functions (Danovaro et al., 2008, 2016; Thurber et al., 2014). Biodiversity is often heralded as necessary to provide most ecosystem services (ES), i.e. the contributions to human well-being from ecosystems, and is used as a proxy for measuring these services (Palumbi et al, 2009; Cardinale et al., 2012). In this paper, biodiversity will be discussed as a component of ecosystem structure because it has been shown to contribute to ecological function and ES capacity (Worm et al., 2006; Harrison et al., 2014; Yasuhara et al., 2016). The relationship between biodiversity and ES remains unclear in many cases (Balvanera et al., 2014; Bennett et al., 2015), perhaps even more so in the deep sea where biodiversity is not yet well characterized

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(Higgs and Attrill, 2015; Sinniger et al., 2016). However, one of the largest anticipated deep-seabed mining (DSM) impacts is loss of biodiversity and its contribution to ES should not be ignored.

Many of the ecological functions that ecosystem structure supports can ultimately be translated into ES. For example, seamount-trapped, vertically-migrating zooplankton (structure) can provide trophic support (function) for fish catch (service) (Clark et al., 2010). Another example is deep-sea infauna (structure) that facilitate the burial of carbon in deep sediments via bioturbation (function), which contributes to carbon sequestration and climate regulation (service) (Xiao et al., 2010). The publication of the Millennium Ecosystem Assessment (MA) (2005) stimulated interest in examining ES and developing ES frameworks for environmental decision-making (Fisher et al., 2009). ES try to associate values with environmental benefits that are linked to human well-being, whether a market exists for the benefit or not. Sustainable management of resources requires that these values are incorporated into environmental regulation.

Deep-sea exploration began in the 1800s but exploitation of its natural resources is a more recent development. There is a growing list of anthropogenic impacts in the deep sea (Ramirez-Llodra et al., 2011) which can result in the loss of ES, including ES yet to be discovered. Fisheries are encroaching deeper into the water column and on the seabed (Morato et al., 2006; Watson and Morato, 2013). The overexploitation of fisheries species by direct targeting or removal as bycatch may cause deep-sea fish populations to decline precipitously. Population declines and crashes may have longer-lasting effects in the deep sea relative to shallow water because life spans are much longer at great depths (Devine et al., 2006; Norse et al. 2012). In addition, trawl fisheries cause physical disturbance and removal of habitat, leaving coral rubble and trawl marks (Roberts, 2002; Puig et al., 2012; Buhl-Mortensen et al., 2015). The removal of three-dimensional habitat structure on the bottom causes loss of associated species that are very slow or unable to recover (Althaus et al., 2009; Williams et al., 2010). Trawling also alters sediment flux and re-suspends sediment in the water column, which can lead to lower biodiversity and ecological function (Martín et al., 2014; Pusceddu et al., 2014; Oberle et al., 2016).

Oil and gas exploration and drilling are now taking place in increasingly deeper waters (Merrie et al., 2014). The infrastructure and extraction of these energy resources have direct impacts on the deep seafloor (Continental Shelf Associates, Inc., 2006). With deeper oil comes an increasing risk of oil spills (e.g. *Deepwater Horizon*, Reddy et al., 2012; Merrie et al., 2014), which have the potential to result in both the loss of deep-sea habitats (White et al., 2012; Fisher et al., 2014), as well as losses of ES in shallow water and coastal systems (Lin and Mendelssohn, 2012).

With accelerating exploration claims in both national and international deep waters, DSM is expected to commence in the near future. Since the first exploration contracts were signed in 2001 (Lévy, 2014), the International Seabed Authority (ISA) has approved 27 contracts in the Pacific, Atlantic, and Indian oceans for polymetallic sulfides, ferromanganese crusts, and polymetallic nodules. Eighteen of these contracts were granted within the last five years (Wedding et al., 2015). The ISA was established by the United Nations Convention on the Law of the Sea (UNCLOS) and governs the minerals and environment in the "Area," defined as the seabed beyond national jurisdiction (UNCLOS, 1982).

Regulation exists for the exploration of polymetallic sulfides, ferromanganese crusts, and polymetallic nodules, but it is not yet in place to ensure the protection of the environment under commercial exploitation (ISA, 2015, 2016). The ISA has made recommendations regarding baseline data collection and monitoring plans (ISA, 2013a), but environmental regulation is still under development. Because commercial DSM has yet to begin, there is an opportunity to incorporate ES indicators into data-collection requirements in all phases of environmental management and decision-making. An ES framework can provide guidance on how valuable services might be maintained while still yielding benefits from the direct extraction of natural resources.

The objectives of this paper are to (1) review ES associated with deep-sea mineral resources and their host habitats; (2) propose practical steps to build ES into environmental planning of DSM; this includes the identification of potentially vulnerable ES, the role of ecosystem structure and ecological function in providing ES, their use as ES indicators, and the valuation of ES; (3) indicate management phases where ES could be incorporated; and (4) identify scientific knowledge gaps that must be addressed to implement an ES framework for DSM regulation.

2. Application of an ecosystem services approach to the deep sea

ES are the contributions to human well-being from ecosystems. MA (2005) categorizes ES into four groups: provisioning, regulating, cultural, and supporting. Provisioning services are the outputs and products obtained from ecosystems; examples include fish and invertebrate catch, pharmaceuticals, and industrial agents (MA, 2005). There is some controversy over the inclusion of abiotic resources as provisioning services because their formation does not involve biotic processes and the timescale associated with their formation is extremely long. Our focus here is on the role of biotic ES in decision-making and planning, partly to identify areas where biotic ES losses can be minimized while still allowing extraction of abiotic resources. Regulating services are benefits from the regulation of environmental processes (MA, 2005). A deep-sea example would be promoting carbon sequestration through transport of carbon to the seabed for burial via the biological pump and diurnal vertical migrations. Another example includes biological regulation, which here will refer to the biological control of populations and pests (Armstrong et al., 2012). Cultural services are non-material benefits that include educational opportunities, aesthetic considerations (e.g. inspiration for the arts), the utility obtained simply from knowing the resource exists, and that the public is being a good steward of the resource for both the current and future generations. The underlying motive for valuing ES is, in many instances, maintaining the option to use these ES at some point in the future. The concept of quasi-option value, where investments are made in scientific research to improve knowledge of the ES, is particularly relevant because knowledge concerning deep-sea ES is often quite limited (Carson et al., 1999). When extractive activities pose the threat of irreversible harm, this consideration can be particularly large. The MA also defines supporting services as those necessary for the production of all other ES, which includes primary and secondary production, and element and nutrient cycling (MA, 2005).

A number of alternative classification systems for ES exist (e.g. Böhnke-Henrichs, et al., 2013; Landers and Nahlik, 2013; Liquete et al., 2013). Two that are commonly used are The Economics of Ecosystems and Biodiversity (TEEB) and the Common International Classification of Ecosystem Services (CICES). TEEB defines function as a subset of ecological processes with the potential or capacity to provide a service. Services are then defined as the realization of the function that provides a benefit to human well-being (de Groot et al., 2010). CICES defines final ES as contributions to human well-being while ecosystem goods and benefits are created or derived from final ES (Haines-Young and Potschin, 2013). Unlike the MA, both TEEB and CICES exclude supporting services from their classification, although both systems acknowledge their importance. What TEEB and CICES define as

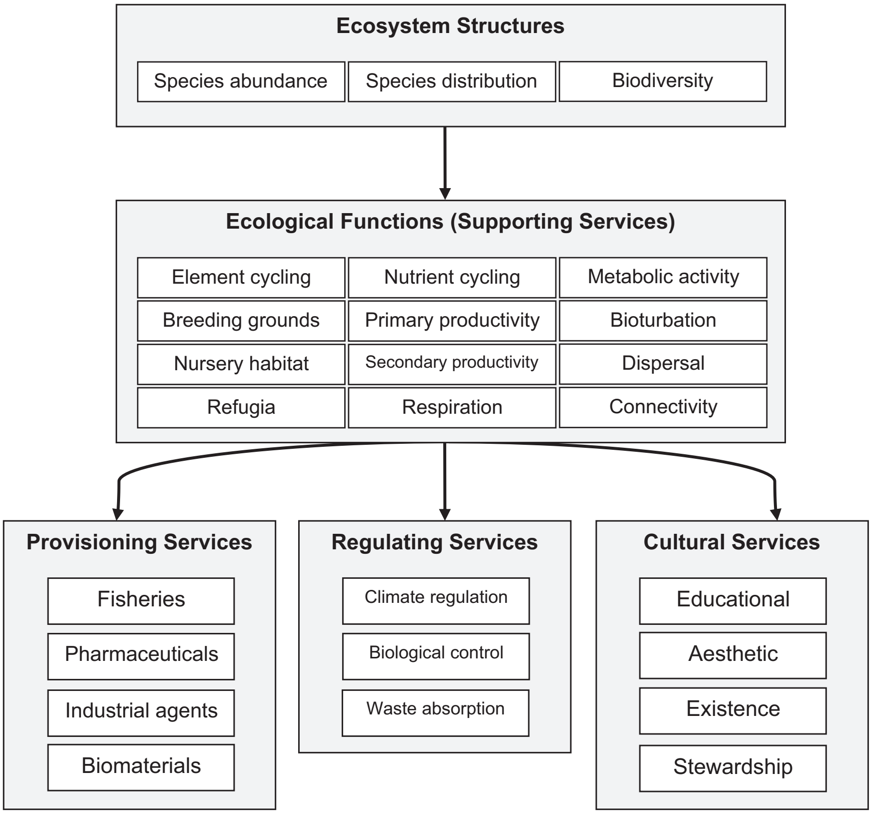

Fig. 1. An overview of linkages between biological ecosystem structures, ecological functions (supporting services), and the ecosystem services (provisioning, regulating, and cultural) they support.

"function" is similar to the MA category of "supporting service," as both are characterized as ecological processes that contribute to ES capacity. It has been argued that the value of supporting services is included in the value of the final services to which they contribute and including them separately would result in double-counting (Boyd and Banzhaf, 2007; Fisher et al., 2009) and an overestimate of economic value. Both the TEEB and CICES systems include instead a distinction between service and benefit to avoid double-counting and to acknowledge that multiple benefits can be derived from one service (e.g. fish and invertebrate catch can provide both food and livelihoods). However, this paper will consider services and benefits together for simplification.

For this discussion we will use a modified form of the TEEB classification system (Fig. 1). ES are the direct and indirect contributions to human well-being, which are grouped into three categories: provisioning, regulating, and cultural. The TEEB considers habitat, including life-cycle maintenance and gene pool protection, its own category of ES but this paper will consider elements within this category as functions (or supporting services as defined by the MA), i.e. ecological processes with the potential or capacity to provide a service. ES are the results of ecological functions that are supported by ecosystem structure defined as the physical, chemical, and biological characteristics of a system. For example, the corals and sponges on seamounts acts as habitat and aggregate fish and their prey (structure), generating trophic interactions and secondary production (functions). These interactions result in fish catch (service), leading to economic and social welfare in the form of food provision and livelihoods. If structure and function are not explicitly identified and protected, then the service may not continue. Ecological functions (supporting services) may be of elevated importance in the context of DSM. Their inclusion in economic valuation can increase estimates of the benefits of alternative development options that are less disruptive. It is essential to highlight their contribution to final ES in order to correctly assess the value of protecting them.

DSM impacts could potentially affect these components of ES provision directly or the linkages among them. Linkages among structure, function, and service must be understood to predict how DSM will affect the provision of ES. Understanding the translation between structure and function and between function and service is essential in order to develop optimal ES indicators, calculate the value of environmental damage, and provide a more complete knowledge of deep-sea processes.

An ES approach has been previously applied to conservation of terrestrial and shallow-water systems, including forests (e.g. Chazdon, 2008; Seidl et al., 2016), coral reefs (e.g. Farber et al., 2002; Rogers et al., 2015), and wetlands (e.g. Aburto-Oropeza et al., 2008; Gunderson et al., 2016) among many other examples. These ecosystems have been and are still subject to destructive practices, including deforestation, coral dynamiting, and conversion to shrimp farms. Incorporation of an ES perspective into environmental decision-making can initiate re-evaluation of these practices. For example, the deforestation of coastal mangroves in the Gulf of California destroys nursery habitat for commercially-important fish species, resulting in loss of profit for local fisheries (Aburto-Oropeza et al., 2008). Despite its integral role in supporting a profitable fishery, the ES of nursery habitat by mangroves was previously ignored.

Linkages between shallow-water ecosystems and human well-being are much better defined than the linkages between deep-sea ecosystems and human well-being. Wetland habitats may provide some similar services as the deep sea such as genetic resources and carbon sequestration (Chmura et al., 2003). However, because they are in closer proximity to human establishments, wetland habitats also provide more direct services, such as coastal storm and surge buffering, shoreline stabilization, and flood prevention

(Koch et al., 2009; Barbier et al., 2011; Gedan et al., 2011), in addition to waste absorption and climate regulation, which are also provided by the deep sea (Armstrong et al., 2012; Thurber et al., 2014). These well-defined services have helped support wetland conservation, such as the U.S. no net wetland loss policy (U.S. Fish and Wildlife, 2002). The conservation value of wetlands will be seen as increasingly important as wetland climate mitigation potential is recognized (Mcleod et al., 2011; Hopkinson et al., 2012). Whether this holds true for the deep sea remains to be seen (Levin and Le Bris, 2015).

Deep-sea ES differ from terrestrial and shallow water ES because the structures and functions (supporting services) that support them, and consequently the ES they provide, are thought to be largely non-restorable. The restoration of DSM sites will be extremely costly with questionable success because of the inaccessibility of the deep sea and lack of knowledge regarding how it functions (Van Dover et al., 2014a). Deep-sea ES are distinct from many other marine and terrestrial systems because (a) there is a large spatial separation between where the service is provided and the stakeholders benefitting from it; (b) many deep-sea processes operate on extremely long time scales (McMurtry, 2001; Devine et al., 2006); and (c) there are significant unexplored and undiscovered constituents and processes in many deep-sea habitats (Ramirez-Llodra et al., 2010). These unknowns can have potentially large-scale consequences if the extraction of deep-sea minerals results in the loss of an undiscovered ES integral to human well-being. A better understanding of the deep sea must be established in order to preserve both use and non-use value provided by its many habitats and species. Because commercial mining has not yet started, the ISA has the opportunity to implement a system for evaluating ES impacts from the start rather than after serious problems arise, as has typically been the case with other ecosystems (e.g. terrestrial forests).

The concept of ES has not been widely applied to deep-sea resource management. Both Boschen et al. (2013) and Collins et al. (2013) address environmental management for polymetallic sulfide mining at hydrothermal vents, but do not mention ES in their recommendations. Van Dover et al. (2014a) do include compensation for harm to ES as a potential source of funding for deep-sea restoration.

One of the few examples of the application of ES to deep-sea resources comes from Batker and Schmidt (2015), who use terrestrial mining metrics as a template for assessing DSM impacts at the Solwara I hydrothermal vent, a polymetallic sulfide site in Papua New Guinea. This report was commissioned by Nautilus Minerals as a preliminary examination of ES that may be impacted by the Solwara I project. The authors conclude that DSM is necessary to meet global demand for copper and will impact ES to a lesser extent relative to terrestrial mines. The use of terrestrial mining metrics for comparison in this report has drawn criticism from Rosenbaum and Grey (2015, http://www.deepseaminingoutofourdepth.org/wp-content/uploads/accountabilityZERO_web.pdf). Some of the terrestrial ES used in the assessment, such as water supply and soil formation, are not relevant to the deep sea. Unique deep-sea ES, like the cycling of sulfur and iron (Tagliabue et al., 2010; Resing et al., 2015) or industrial agents (Mahon et al., 2015), are overlooked. Deep-sea ES that have not been discovered but potentially exist (based on findings in other reducing ecosystems), such as novel nursery grounds (Levin et al., 2016), food provision, and pharmaceuticals, were assumed to have no economic value. Although the Solwara I project is one site, it is important to consider its impacts in conjunction with the possibility of additional deep-sea activities in the region which are actively being planned, e.g. the Solwara 12 project by Nautilus Minerals (Golder Associates, 2012) as well as their exploration work in Tonga and the Solomon Islands and deep-sea mine tailings placement in Papua New Guinea (Shimmield et al., 2010). There are also potential inconsistencies within the report. For example, Batker and Schmidt (2015) state that hydrothermal vents are unique systems with endemic species but then later say that the DSM impact on genetic resources will be low. The assessment treats Solwara I as an isolated system and does not examine its larger role in the deep sea via connectivity to other systems. Lessons learned from terrestrial mines and shallow water systems *can* be incorporated into DSM environmental management, but attributes unique to the deep sea should be considered while assessing impacts and developing regulation. There are also important aspects of the regulatory framework that need to be implemented due to the international nature of relevant resources and ecosystems.

3. Ecosystem services associated with deep-sea mineral resources and their host habitats

Of the four primary mineral resources that are being considered for DSM, phosphorites occur primarily within national jurisdictions and are owned by nation states. Polymetallic sulfides, ferromanganese crusts, and polymetallic nodules occur both within national jurisdictions and in international waters. Those mineral resources in the Area are under the jurisdiction of the ISA and are considered the common heritage of mankind by the ISA in accordance with UNCLOS, Article 136 (UNCLOS, 1982; Jaeckel et al., 2016a). Article 140 further states that all activities in the Area should be done for “the benefit of mankind as a whole” (UNCLOS, 1982). By definition, ES contribute to human well-being, generating multiple values to society which include economic gains (e.g. from fisheries), social progress (e.g. education and art), and ecological sustainability (e.g. resilience and adaptation). Although ES valuation often includes economic and social indicators, ecological sustainability is rarely considered. In order to ensure benefits to mankind as a whole, all values must be factored into the development of DSM regulation by the ISA and ES provide a useful tool to do so.

The identification of stakeholders is an important step to developing DSM regulation that benefits mankind as a whole. The use of an ES framework can help identify relevant stakeholders through mapping tools and valuation studies. Stakeholders benefitting from provisioning services may differ from those benefitting from regulating or cultural services. Stakeholders may have different values with competing objectives, and the ES of concern may emerge at different spatial and temporal scales. For example, many provisioning services may happen at the scale of a vent or a seamount while regulating services emerge at larger, landscape spatial scales or long time scales, and can be more diffuse. Identifying stakeholders may facilitate independent review and public participation in environmental impact assessments for DSM (Lallier and Maes, 2016).

In its current and draft regulations, the ISA invokes the precautionary principle as outlined in the Rio Declaration, which states that a precautionary approach should be widely applied with scientific uncertainty as an invalid reason for delaying measures to prevent environmental degradation (Rio Declaration, 1992). The precautionary principle should be applied “as far as reasonably possible” by the ISA, sponsoring States, and DSM concession holders. What is needed is a clear articulation of the how the precautionary principle will be operationally implemented (Majone, 2002; Jaeckel, 2016b). There are a range of unknowns regarding the environmental impacts of DSM that need to be considered and ideally avoided before large-scale exploitation of deep-sea mineral resources begins (Nautilus Minerals Nuigini Limited, 2008; Schmidt, 2015).

3.1. *Polymetallic sulfides*

Polymetallic sulfides are found at hydrothermal vents where water circulates through oceanic crust, at spreading centers, back-arc basins, and volcanic arcs (Petersen et al., 2016). As the fluids are heated by magma, metals in the crust are leached into the water and expelled from black smokers, where they precipitate upon contact with cold seawater. These sulfides form large deposits of varying sizes and are rich in minerals including zinc, lead, barium, silver, and gold (Boschen et al., 2013). These have triggered a deep-sea “gold rush” (Ramirez-Llodra et al., 2011; Merrie et al., 2014; Petersen et al., 2016), but the profitability of these extractive activities is still being debated.

Vent communities can be dominated by large clams, mussels, snails, and siboglinid tubeworms (Ramirez-Llodra et al., 2007). These species produce carbonate shells and chitinous tubes (Ruan et al., 2008) that provide structure and create substrate at vent sites. This structural diversity can lead to more available niches and, ultimately, greater biodiversity (Govenar, 2010). The biogenic structures of these organisms may be used by non-vent fauna once the active flow ceases (Levin et al., 2016). There are also endemic vent fauna that further contribute to deep-sea biodiversity (Nakajima et al., 2015), which can influence ES. Tubeworm hemoglobin as a template for artificial blood (Flores et al., 2005) and unique armor inspired by scaly foot snails (Yao et al., 2010; Blaustein, 2010) are examples of how the faunal biodiversity might translate into provisioning services.

In addition to contributing to deep-sea biodiversity, vent microbial communities appear to play a key role in regulating services, such as the global cycling of carbon, sulfur, and potentially heavy metals (Jeanthon, 2000; Meyer-Lombard et al., 2013). Vents are areas of high productivity due to the presence of chemosynthetic microbes that transform and recycle carbon (Dubilier et al., 2008). Microbes and symbiont-bearing animals can consume sulfide, and methane (which could act as a greenhouse gas if released into the atmosphere) (Jørgensen and Boetius, 2007). Vent microbes hold potential for biotechnology advancement, particularly for industrial applications at high temperatures. Examples of thermophile applications include DNA polymerases for polymerase chain reaction (Terpe, 2013) and anhydrases for carbon dioxide scrubbing (Fig. 2A) (Mahon et al., 2015). Other applications include use of lipases, pullanases, and proteases for detergent, food processing and waste treatment. Amylases are used for baking and brewing, and xylanases and cellulases are used for pulp and paper processing and recycling (Leary, 2004). These biological compounds may provide provisioning services (new products), regulating services (global iron cycling (Tagliabue et al., 2010; Resing et al., 2015)), and cultural services. Unfortunately at this point in time, many if not most ES derived from vent microbes and organisms remain to be discovered or identified.

3.2. *Ferromanganese crusts*

Ferromanganese (or cobalt) crusts form as minerals precipitate out of seawater onto exposed hard substrate. These minerals include cobalt, nickel, platinum, thallium, and tellurium (Hein et al., 2000). Some of these rare metals are used for photovoltaic solar cells, hydrogen fuel cells, electric car batteries, computer chips, cell phones, and other technology (Hein et al., 2013). They are often found on seamounts throughout the global ocean, with deposits having the greatest commercial potential at 800–2500 m water depth (Yesson et al., 2011). Crust formation proceeds at very slow rates on the order of millimeters per million years (Usui et al., 2007).

Seamounts also provide hard attachment substrates used by sessile cnidarians and sponges to extend above the boundary layer (Hoff and Stevens, 2005; Schlacher et al., 2014), creating reefs or gardens and supporting a host of biodiversity (Auster et al., 2005; Cathalot et al., 2015). The coral and sponges also provide an ecological function (supporting service) in the form of nursery habitat (Baillon et al., 2012). The three-dimensionality of seamounts accelerates water flow and concentrates food particles, creating local areas of higher productivity and higher biodiversity relative to surrounding areas (Morgan et al., 2015). This high productivity provides provisioning services in the form of fish catch by attracting mobile organisms, such as commercially-fished orange roughy and oreo that aggregate around seamounts (Fig. 2B), as well as sharks, billfish, and other pelagic predators (Hughes, 1975; Koslow, 1997; Morato et al., 2010). Some organisms on seamounts provide templates for novel biomaterials. For example, bamboo corals are a model for synthetic human bone replacements (Ehrlich et al., 2006) and sponge spicules are superconductors for light (Brummer et al., 2008).

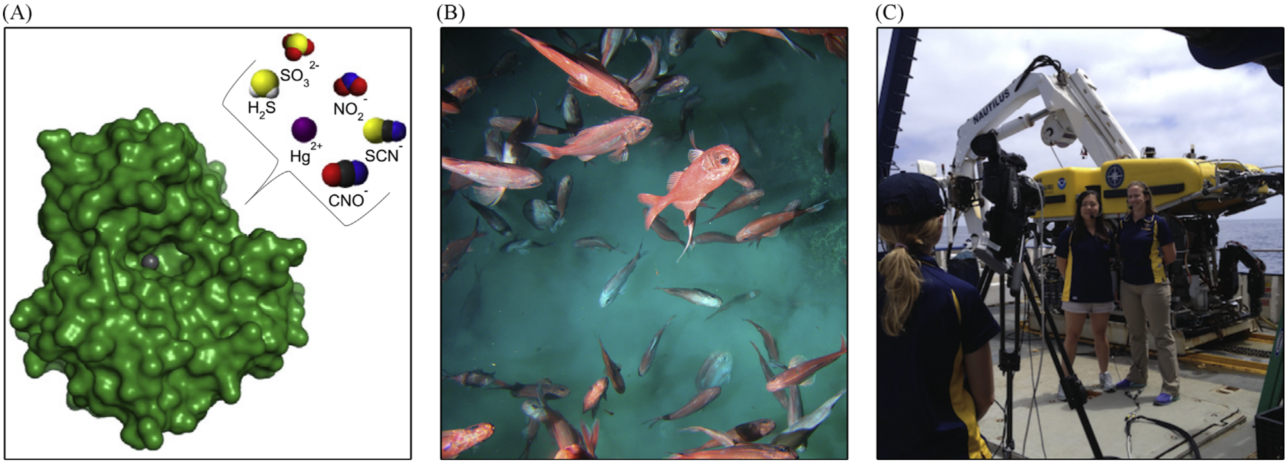

Fig. 2. Examples of deep-sea ecosystem services. (A) Provisioning service of industrial agents – Carbonic anhydrase from a hydrothermal vent bacterium proposed for industrial carbon dioxide scrubbing; image from Mahon et al. (2015). (B) Provisioning service of fish catch – A spawning aggregation of orange roughy (*Hoplostethus atlanticus*), a commercially-fished species, on the summit of a protected seamount at 890 m on New Zealand's Chatham Rise; photo courtesy of New Zealand's National Institute of Water and Atmospheric Research and the Ministry for Primary Industries. (C) Cultural service of education – A live-stream from scientists on the E/V Nautilus to K-12 students onshore, sponsored by Ocean Exploration Trust; photo courtesy of L.A. Levin.

3.3. Polymetallic nodules

Polymetallic (or manganese) nodules were first discovered in 1873 during the *H.M.S. Challenger* expedition. They are found on the abyssal plains beneath areas of low productivity, such as the eastern Pacific Ocean and the Indian Ocean (Petersen et al., 2016). Each nodule begins as a small, hard fragment of debris (e.g. tests or shells, shark teeth, other nodule fragments), and grows when dissolved metals precipitate on its surface. These metals include manganese, nickel, titanium, vanadium, cobalt, and iron, and are in increasing demand for modern electronic applications and green technologies such as thermal cooling devices and chemical sensors (Hein et al., 2013). Nodule formation is very slow; in the Pacific, growth is 1–2 mm per million years (McMurtry, 2001). Despite their slow formation, nodules can be found at densities greater than 10 kg/m^2 in the Clarion–Clipperton Fracture Zone in the eastern equatorial Pacific (Morgan, 2000).

The biological communities associated with nodule provinces are far less dense and have lower biomass relative to hydrothermal vents and seamounts, but host a greater diversity of infauna and epifauna including polychaetes, echinoderms, and crustaceans (Mullineaux, 1987; Howell et al., 2002; Brandt, 2005; Glover et al., 2001, 2015, 2016). A portion of these organisms show some degree of endemism, contributing to deep-sea biodiversity (Rex et al., 2005; Rex and Etter, 2010). The nodules provide hard substrate, creating available niches for specialized fauna (Thiel et al., 1993; Veillette et al., 2007; Vanreusel et al., 2016). In addition, the presence of hard substrate in an expansive area of soft sediment can be an important conduit for genetic resources (Janssen et al., 2015). The ES associated with nodule provinces may be related to the vast area where carbon is sequestered, and the high diversity of small, often rare eukaryotes with currently unknown functions and capabilities.

3.4. Phosphorites

Phosphorites are primarily found in shallow sediments on continental margins where upwelling occurs and surface production is high, such as the California, Humboldt, Canary, and Benguela current systems (Baturin, 1971; Föllmi, 1996). Due to low oxygen content in the upwelled waters, a substantial amount of organic matter reaches the sediment, setting the stage for phosphorite formation which is thought to be mediated by bacteria (Baturin, 1971; Schulz and Schulz, 2005). Phosphorite deposits are rich in phosphorous, calcium, and fluoride and are widespread on continental margins (Baturin, 1971).

There is current interest in mining phosphorite mineral deposits on the shelves and slopes of Namibia, South Africa, New Zealand, and Mexico. The phosphorite beds in these areas tend to be poorly characterized with respect to small biota and microbes, which may have value as genetic resources due to their unusual tolerance of extreme anoxic or sulfidic conditions. There is concern that DSM may make permanent changes to benthic systems that are vital for the reproduction, feeding, and survival of key species (Leduc et al., 2015). This concern appears to be particularly relevant because phosphorites have relatively low value, suggesting that large areas need to be mined in order for this type of DSM to be profitable. Continental margins with phosphorites support productive fisheries and are also subject to oil and gas drilling, shipping, and use by species with high conservation value, such as marine mammals and turtles (Findlay et al., 1992; Reeves, 2000; Campbell and Smith, 2006).

These four targeted mineral resources provide some similar ES: biodiversity (structure which contributes to genetic resources, potential for adaptation, and resilience), carbon sequestration (Feely et al., 2001), cultural services (Fig. 2C), and the unknown. For example, 188 natural products from marine fauna (found at depths ranging from 50 m to >5000 m) have been described since 2008, including compounds used to treat cancer and infectious diseases (Skropeta and Wei, 2014). Although these ES are shared, they are distinct among habitats, and perhaps even within the same type of habitat, i.e. for endemic species. For example, though vents and seamounts both contribute to deep-sea biodiversity, they cannot be substitutes for each other in the context of biodiversity because they host different communities of organisms. Each habitat provides a different magnitude of ES that operates on varying spatial and temporal scales, and will experience distinct impacts from mining.

The proposed mining process is reasonably similar across the different mineral resources. In general, the resource is cut (excluding nodules), aggregated, pumped to the surface, settled, and then excess sediment and seawater is expelled. Each of these processes affect ES through direct physical disruption, changes in substrate, light, noise, sediment plumes, smothering, release of contaminants, and changes in biogeochemistry (Oebius et al., 2001; Nautilus Minerals Niugini Limited, 2008; SPC, 2012). These effects will interact to change ES, altering productivity, connectivity, rates of extinction, and other characteristics of the ecosystem (Nautilus Minerals Niugini Limited, 2008; McClain and Barry, 2010; Van Dover, 2014b). Depending on the indicator used, it may be impossible to distinguish which specific impact of the production process is altering a given ES (e.g. sediment plume vs. contaminants vs. loss of source propagules).

4. Proposed framework and approach

Werner et al. (2014) uses the Gulf of Mexico to illustrate a practical approach to implementing an ES framework for the oil and gas industry. The authors suggest three steps: (1) prioritize relevant ES, (2) assess indicators of ES capacity, and (3) rank indicators to identify the most effective. The initial steps proposed below are loosely based on suggestions by Werner et al. (2014), with changes that adapt an ES framework to the context of DSM with a focus on valuation and implementation.

4.1. Identification of potential DSM impacts on ES

Deep-sea ES have been broadly described (Armstrong et al., 2012; Thurber et al., 2014). What is still unknown are which ES will be impacted by DSM and to what extent. Criteria for identification of vulnerable ES could include sensitivity to disturbance (from DSM and cumulative impacts), recovery and restoration potential, existence of possible substitutes, and synergistic effects on other ES. Although similar disturbances may result from extraction of the different mineral resources, each impact may manifest differently among habitats. Information about physiology and metabolism, dispersal and connectivity, nutrient and element cycling, and life histories is imperative to uncover details about structure, function, and, ultimately, the ES they provide. It is also important to acknowledge the strong likelihood for discovery of new ES. This is something rarely considered in decision-making and is of lesser concern with more widely studied ecosystems where there is a long history of human activity.

4.2. Consideration of the role of ecological functions (supporting services)

By definition, ecological functions (supporting services) are necessary for the provision of final ES (de Groot et al., 2010). They derive from structural characteristics of the ecosystem (Table 1), and need to be identified and protected in order to preserve ES.

Table 1
Measurable ecosystem structures and ecological functions (supporting services) that support ecosystem services.

Service	Function (Supporting service)	Structure
Provisioning Services		
Fish catch	Breeding or spawning grounds	*Physical structure Adult distribution *Population density/biomass Population age structure
	Nursery habitat	*Physical structure *Flow regime Biotic structure/ecosystem engineers Egg, larval, and juvenile abundance Prey abundance
	Refugia	*Physical structure *Flow regime *Population density/biomass Biotic structure/ecosystem engineers
	Secondary production Trophic support	Feeding locations *Organic matter flux (e.g. via sediment traps) *Benthic community composition Prey abundance Food web structure (e.g. via *stable isotope analysis, gut content analysis) Growth rates
	Dispersal *Connectivity	*Flow regime (e.g. via passive transport models) *Hydrography Endemicity Life-history traits Larval distribution, temporal patterns Larval density
Pharmaceuticals Industrial agents Biomaterials	Biodiversity	*Physical structure *Hydrography *Faunal characterization (e.g. mega, macro, meio, protozoa) *Microbial characterization Genetic diversity
	Metabolic activity	Physiology *Water chemistry Natural products chemistry *Microbial characterization Microbial transcriptomics & metabolomics Faunal metabolomics
Regulating Services		
	Surface photosynthesis	*Phytoplankton density/biomass Photosynthetic pigments Nutrient concentrations
	Chemosynthesis	*Water chemistry *Microbial characterization Symbiotic relationships
	Remineralization	*Microbial characterization Phaeopigments *Water chemistry
	Carbon flux	*Plankton community composition
	Bioturbation Bioirrigation	*Sediment properties (e.g. grain size, C_{org}) *Sediment community composition Sediment Radiochemistry: Pb-210, Th-234 *Pore-water chemistry
Climate regulation – methane sequestration	Aerobic methane oxidation	*Water chemistry (e.g. methane concentration) Methanotrophic bacteria characterization in water and symbiont-bearing fauna
	Anaerobic methane oxidation	*Water chemistry (e.g. methane concentration, sulfate concentration) Methanotrophic archea characterization Sulfate-reducing bacteria characterization Authigenic carbonates
Climate regulation – greenhouse gas regulation	Nitrogen fixation Nitrification Denitrification Nitrate reduction Ammonium oxidation	*Organic matter flux *Nutrient concentrations in water and pore-water *Pore water chemistry *Microbial characterization
Biological control of populations		Pest density/biomass & distribution Predator density/biomass & distribution Viral abundance Food web structure
Waste absorption	Assimilation Metabolic activity	*Water chemistry *Baseline level of toxins (e.g. trace metals, polycyclic aromatic hydrocarbons) Physiology *Faunal characterization *Microbial characterization
	Bioturbation Bioirrigation	See above.
Cultural Services		
Educational Aesthetic including the arts Existence Stewardship	All functions, and subsequently structures, contribute to some aspect of cultural services. However, how these services are perceived and prioritized are dependent on factors such as cultural background and socioeconomic status, as well as the communication of deep-sea science and issues (e.g. via news articles, visuals).	
Other ecological functions		
	Element and nutrient cycling Iron oxidation Manganese oxidation Sulfur oxidation Sulfate reduction	*Trace element concentrations in water and sediment *Nutrient concentrations in water and pore-water *Pore water chemistry *Microbial characterization

Structures and functions annotated with an asterisk (*) are explicitly included in the International Seabed Authority environmental impact assessment recommendations for exploration for seabed minerals in international waters (ISA, 2013a).

The types of information and measurements necessary to identify and quantify relevant function vary among different deep-sea ES. For example, those necessary to provide fish and invertebrate catch include breeding or spawning grounds, nursery habitat, primary production for trophic support, and refuge from predators. Information regarding life histories is especially important in order to quantify and valuate the final ES, as well as to effectively manage stocks (Adams, 1980; Shuter et al., 1998). Identifying crucial habitat, estimating survival and recruitment rates, and linking larvae and juvenile populations to adult populations are necessary to translate biological measurements into economic value (Botsford et al., 2009). Another example includes carbon sequestration, which is influenced by functions such as primary productivity (Kuypers et al., 2002), carbon flux to the bottom (Jahnke, 1990), degradation and burial rate of organic carbon (Hartnett et al., 1998; Breithaupt et al., 2012; Smith et al., 2015). These measurements will help estimate the capacity for deep-sea carbon sequestration, which can then be used for valuation studies and mitigation planning. Information regarding deep-sea functions can be used to develop ecosystem principles, which become an educational element in ES valuation (Jobstvogt et al., 2014a). However, lack of data and knowledge regarding deep-sea structure and function often makes full characterization challenging.

Some functions (supporting services) may be an input to multiple final ES. For example, production can influence fish and invertebrate catch via trophic support, and carbon sequestration via subsequent export to depth. Both the direct and indirect impacts, as well as downstream consequences of DSM may affect the ability of targeted habitats to provide ES through channels still unknown. These knowledge gaps invoke the use of a precautionary approach, and may in some instances suggest the postponement of large-scale DSM until these relationships are better understood.

4.3. *Developing ES indicators*

Practical ES indicators need to be developed as requirements for baseline data collection and monitoring programs. Werner et al. (2014) establishes criteria to assess ES indicators. Lagging indicators detect ES changes after they occur and are useful in establishing the level of impact on a service. Leading indicators provide information about structure, function, and potential sources of change. Structures and functions themselves may serve as indicators of ES (e.g. Table 1). For example, water turbidity and flow regime may foreshadow impacts from sediment plumes caused by DSM (e.g. suffocation, preventing larval settlement (Jones, 1992)). Indicators should be practical, sensitive, and easy to monitor in order to facilitate implementation into baseline data collection and monitoring programs. Different indicators for the same ES may be more practical in one setting versus another. For example, indicators for carbon sequestration may differ between a nodule province and a phosphorite-rich margin due to the large difference in area over which carbon is sequestered. One might rely on satellite-based surface chlorophyll measures to integrate over large areas while the other could use time-series sediment trap data; both would involve radioisotope-based sediment accumulation measures. Indicators should be quick to respond to changes in ES. The measurements should be taken accurately using a standard protocol over spatially-relevant scales in order to statistically analyze the obtained data. Consistent methods and reliable data are important inputs for making good policy decisions and are convincing to policymakers. Once ES indicators are developed, they can be used to monitor changes in ES and their value (Boyd et al., 2014).

4.4. *Valuation of ES*

The literature on valuation of environmental goods and services is large (Hanley and Barbier, 2009), but its application to the deep sea has been extremely limited (e.g. Table 2). Wattage et al. (2011) and Jobstvogt et al. (2014b) attempt to estimate the value of deep-sea corals and biodiversity, respectively, using stated preference methods that ask individuals for information related to their economic value for a non-market good or service (in contrast to revealed preference methods that infer values from consumer and firm behavior). Both studies ran into challenges. The public lacks knowledge about the deep sea, but more important, scientific uncertainty is sufficiently large that it is difficult to comprehensively describe changes in ES in a way that is readily understandable to a lay audience. From a stated preference perspective, it is possible to describe a policy that changes one or more ES, and ask the public to value that policy. However, it is important to realize that only the ES in the survey will be valued. The ecosystem principles approach presented by Jobstvogt et al. (2014a) offers an expert consensus approach to development of principles that link function (supporting services) to service, for use in educating the public prior to a valuation survey.

Table 2
Valuation methods typically used for different categories of ecosystem services

Service, function, or structure	Typical valuation method	Example
Provisioning Services Fisheries Pharmaceuticals Industrial agents Biomaterials	Market value Avoidance cost	1. **Market value of pharmaceuticals** (Erwin et al., 2010) 2. **Market value of coldwater coral fisheries** (Foley et al., 2011) 3. **Market value of fisheries** (Martin et al., 2016)
Regulating Services Climate regulation Biological control Waste absorption	Avoidance cost Replacement cost Production function approach Hedonic pricing Contingent valuation	1. Avoidance cost of carbon dioxide (Beaumont et al., 2008) 2. Avoidance cost of biological regulation (Zhang and Swinton, 2012)
Cultural Services Aesthetic Educational Existence Stewardship	Hedonic pricing Contingent valuation	1. CV of bequest value (O'Garra, 2009) 2. **Value of scientific investment** (Godet et al., 2011) 3. Choice modeling of stewardship value (Lim et al., 2015)
Ecological Functions (Supporting Services) Element/nutrient cycling Productivity/respiration Metabolic activity Habitat provision Bioturbation & C burial Dispersal/connectivity Biodiversity (ecosystem structure)	Production function approach Contingent valuation	1. **CV of coldwater corals** (Glenn et al., 2010; Wattage et al., 2011) 2. **CV of biodiversity** (Jobstvogt et al., 2014b)

Examples specific to the deep sea are in bold. CV is an abbreviation for contingent valuation.

The estimated value of an ES is highly dependent on the population being sampled and survey scenario. Preferences for particular policies often differ systematically by age, culture, education, environmental attitudes, gender and race. This may lead to different sample populations placing different values on the same ES. How to aggregate value across individuals is well defined in a national context but it is in a nascent state for international resources managed by an international authority like the ISA.

Thinking about implementing a contingent valuation survey raises questions about whether maximum willingness to pay to avoid harm or minimum willingness to accept compensation to agree to the harm is the more appropriate property rights framework. Because the ISA has no ability to tax the public for DSM, the willingness-to-pay mechanism would take the form of higher prices in return for implementing DSM in a manner that is less harmful to the environment. The common heritage of mankind language suggests that minimum willingness to accept compensation is appropriate, but this property right is difficult to reliably implement. How the ISA distributes any revenue can influence this interpretation.

Revealed preference approaches include: (a) using the price of a resource bought and sold in a market, (b) estimating the cost of averting behavior related to an adverse change in an ES, (c) determining the replacement cost of the next best option, (d) estimating how the output of production changes with changes in inputs including ES, and (e) estimating how the price of a marketed product changes as attributes of that product (including

Box 1–Economic valuation methods and examples of potential application to the deep sea.

Market value: Market products are associated with a market and price that reflect their value, e.g. the value of a deep-sea fish species is its market value. These prices should be adjusted for any market imperfections, such as subsidies and barriers to entry.

Averting behavior (avoidance cost): How much is spent to avoid adverse changes in an ES, e.g. a fishing boat may incur extra costs to avoid areas where DSM is taking place.

Replacement cost: How much it would cost to replace an ES with the next best option for providing the same service, e.g. a climate change agreement might require the carbon not buried due to DSM to be sequestered through another channel, which has an associated cost.

Production function approach: Output from a production function depends on its inputs including different ES. The value of a final ES can be determined by how it influences the production output when that output can be valued in economic terms. For example, reducing pollution may increase the growth of a fish stock sold in the marketplace.

Hedonic pricing: The price of a good is seen to be a function of the bundle of its attributes (including ES) of which it is comprised, e.g. price differences between marketed fish with and without traces of DSM contaminants are related to the value of contaminant removal.

Contingent valuation, including choice modeling (CV): A stated preference method that involves surveys regarding maximum willingness-to-pay or minimum willingness to accept compensation for a non-market good or service, e.g. an individual could be asked how much they would be willing to pay to implement a program that protects one or more rare deep-sea species found in nodule provinces.

Benefit transfer: A method of transferring values estimated in a primary study, using one or more of the techniques above, to a similar system. It is often applied to many ES. For example, a study calculating the value of nursery habitat provided by a shallow-water coral reef might be used to estimate the same ES in a coldwater coral reef. Due to the unique nature of the deep sea, there are probably few cases where transfer from shallow water or terrestrial examples makes sense.

ES) are changed (see Box 1 for more details). The major problem with using most of the revealed preference approaches to assess economic impacts of changing ES on consumers and producers is the ability to quantify *all* of the important ES. We are able to identify many (but not all) deep-sea ES and have only just begun to develop methods to quantify them at the level of detail needed for economic valuation purposes.

4.4.1. Other social impacts

There are other social impacts that may need to be taken into account in addition to changes in economic value. Social metrics might include the number of people whose livelihoods depend on a given ES (e.g. fishermen) or the number of people who directly benefit from an ES (United Nations, 2016). These types of measurements may be particularly appealing to policymakers who are concerned with the distribution of policy outcomes and social equity.

4.5. Incorporation of ES into environmental planning and implementation

Significant advances in the environmental planning process are needed before large-scale commercial DSM commences. The following section outlines several steps within the environmental planning and implementation process where ES approaches can be included (Fig. 3), and provides recommendations for the operationalization of ES concepts. As strategic environmental assessments provide a big-picture look at policies and programs, ES mapping could provide a useful tool for assessment of multiple services as well as multiple stressors. Environmental impact assessments are more specific; they look at an activity, involving baseline data collection and monitoring programs that should include measurements to help characterize how ES indicators are changing (Table 1). ES can also be incorporated into environmental management plans that outline methodologies to be used over the course of the activity, by serving as criteria for prioritizing areas for spatial protections and for defining ecological thresholds. The application of ES concepts may be most integral to the development of a mechanism in which the value of lost ES can be used as a measure of the compensation required for damage to the environment.

4.5.1. Strategic environmental assessments

The earliest activities in environmental planning and management include a strategic environmental assessment (SEA), which is the “formalized, systematic, and comprehensive process of evaluating the environmental effects of a policy, plan, or program and its alternatives” (Therivel and Partidario, 1996). SEAs consider all existing activities and human uses, and differ from EIAs in that EIAs generally consider one site-specific activity rather than a policy, plan, or program. Partidario and Gomes (2013) suggest ES incorporation into SEA methodology with three main steps: (1) identify ES and stakeholders, (2) prioritize ES, and (3) perform an ES assessment. It is important that the first and third steps consider appropriate scales. DSM stakeholders may range from individual firms to regional beneficiaries with varying degrees of knowledge and investment. For the third step, spatial and temporal scales will differ greatly among the resources and settings of interest. For example, space and times scales for delivery of climate regulation services in nodule provinces are expansive, whereas services related to fisheries on seamounts may be highly localized. Active hydrothermal vent communities may be able to recover on year to decadal time scales (Tunnicliffe et al., 1997; Van Dover, 2010), but fauna associated with inactive hydrothermal vents, cobalt crusts, or polymetallic nodules could take much longer to recover (Thiel et al., 2001; Smith et al., 2008).

Mapping tools can be used to examine spatial distribution of ES, analyze synergies and tradeoffs between ES, compare ES supply and demand, and prioritize areas for conservation (Maes et al., 2012). There exist many examples of ES mapping (e.g. Raudsepp-Hearne et al., 2010; O'Farrell et al., 2011; Burkhard et al., 2012), but few are from marine systems (e.g. ; Mangi et al., 2011), and none are from the deep sea. Challenges to marine ES mapping include dynamic benthic and pelagic habitats over time, and poor understanding of the processes that occur in them (Maes et al., 2012). The problem of lack of data is even more prominent in the deep sea and highlights the importance of baseline data collection and monitoring requirements. Marine ES mapping can provide a tool to identify areas that may be especially valuable or vulnerable and ensure the proper environmental protections are in place as human activities in the deep sea expand.

4.5.2. Environmental impact assessments

The ISA requires environmental impact assessments (EIAs) in their exploration contracts in order to evaluate the risk to the environment, socio-economic outcomes, cultural resources, and human health (ISA, 2010a, 2010b, 2010c). Based on these assessments, strategies and methods can be proposed to avoid or minimize the likelihood or severity of potential hazards. Current ISA exploration regulation states that activities cannot be

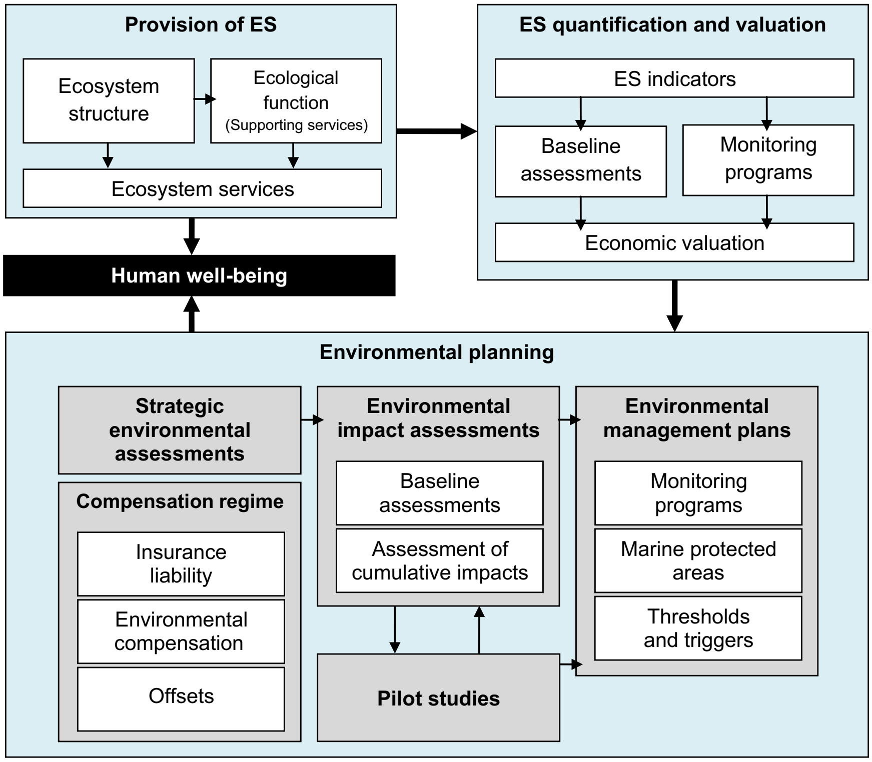

Fig. 3. Relationships among components of ecosystem services, their study, and phases in environmental planning where ecosystem services could be incorporated.

undertaken if there is evidence indicating risk of "serious harm to the marine environment," i.e. the ISA and its concession holders must prevent activities that present "significant adverse changes" (ISA, 2010a, 2010b, 2010c). However, the definition of "serious harm" is under debate (ISA, 2015). ES could serve as one standard for assessing serious harm in the context of DSM EIAs because they link environmental health to human well-being. One recommendation is for EIAs to characterize ES provided by the area of concern, the structure and function necessary to maintain those services, and potential DSM impacts on them. Evaluating DSM impacts on ES will help minimize loss of valuable environmental benefits.

4.5.2.1. Baseline data collection and monitoring programs. EIAs require acquisition of baseline data and the proposal of a monitoring plan (ISA, 2013a). Baseline data collection should include physical, chemical, and biological measurements that serve as ES indicators (which may include measurements of structure and function) or inform about ES to characterize the targeted habitat and its services (see Table 1). Examples of these measurements may be bioturbation rates, respiration rates, and sedimentation rates, which affect carbon sequestration (Vardaro et al., 2009), or concentration of fish larvae of commercial species in the water column (Werner et al., 2014). Deep-sea scientists can play a major role in adjusting current baseline data acquisition practices to better reflect ES by developing shared protocols for characterizing and quantifying ES. It will also be important to standardize these protocols across SEAs, EIAs, and other assessments to produce a better understanding of DSM impacts on ES. ES must first be adequately characterized in order to observe any changes. The establishment of baseline ES provision is necessary to monitor how DSM will affect the natural processes that contribute to human well-being.

When adverse ES changes are observed, compensation for any value lost should be collected by the ISA. How much of this compensation should be provided to major stakeholders who are adversely impacted versus the general public is an open question. Should DSM impacts improve deep-sea provision of some ES, value added could manifest as environmental credits to the concession holder. Current baseline and monitoring measurements recommended by the ISA do not explicitly include ES, but do contain measurements to characterize habitats and biodiversity (see Table 1). Translating these measurements into final ES remains a challenge. In part, this is because DSM can set in motion multiple complex changes. For instance, disturbance of an ES can facilitate the entry of an invasive species, which can potentially increase local biodiversity in an undesirable way, creating an ecosystem disservice or a new or enhanced service that has negative consequences (Zhang et al., 2007).

The first several pilot studies and commercial DSM projects need to be treated as an opportunity to do extensive monitoring in order to determine the effectiveness of ES Indicators, to identify the ES influenced by DSM activity, and to examine the magnitude of impacts. There is a clear learning-by-doing aspect, an economic concept in which practice yields higher efficiency (Ying, 1967) that can help inform future DSM regulation and activity by incorporating the results from these initial studies and projects. An interesting question here is how much of this learning should be paid for by the DSM concession holders, sponsoring nations, and the ISA as the knowledge gained will make future DSM projects easier to assess.

4.5.2.2. Assessment of cumulative impacts. The number of anthropogenic impacts on the deep sea is increasing as commercial interest grows and greenhouse gas emissions continue (Ramirez-Llodra et al., 2011). These may impact deep-sea ES in additive, antagonistic, or synergistic ways (Crain et al., 2008). Mining claims could be made in areas that are ecologically connected or are subject to deep-sea fishing, shipping, waste disposal, pollution, or major climate change impacts (Mengerink et al., 2014; Levin and

Le Bris, 2015). A systematic examination of cumulative impacts on ES could be incorporated into EIAs by determining the impacts of different combinations of multiple mining events, different types of mining, direct human activity, and climate change. There could be spatially disjoint impacts from different stressors acting on different ontogenetic stages of major fishery species or endangered species, which only matter when combined. DSM regulation needs to reflect the possibility of cumulative impacts from multiple mining events (e.g. at multiple claims in the Clarion-Clipperton Fracture Zone and the Mid-Atlantic Ridge), and from non-mining activities that cause more significant changes in ES relative to impacts from DSM alone. This may mean whole suites of ES, ecological functions (supporting services), or ecosystem structures must be protected in order to maintain ES of interest (Koch et al., 2009). One suggestion to minimize cumulative impacts on ES could be to incorporate an ES supply function into existing tools that map cumulative impacts (e.g. Halpern et al., 2008). This could provide insights on what areas may be most valuable to protect and most vulnerable to impacts.

4.5.3. *Environmental management plans*

The draft ISA regulation for commercial DSM will require an environmental management plan (EMP) that outlines methodologies; sampling and archiving before, during, and after operations; measureable criteria; and threshold indicators (ISA, 2015). Incorporation of ES into these aspects of an EMP provides a mechanism to take into consideration the societal value of natural processes.

4.5.3.1. Marine protected areas. ES has a role to play in the identification and designation of areas that are to be protected from mining impacts (e.g. Chan et al., 2006; White et al., 2011). There are several different categories of protected areas being considered in the context of spatial management for DSM. The United Nations defines vulnerable marine ecosystems (VMEs) as populations, communities, or habitats that are “both easily disturbed and very slow to recover, or may never recover” (FAO, 2009a). These VMEs currently include hydrothermal vents (e.g. Reyjkanes Ridge) and seamounts (e.g. Koko and C–H seamounts in the Pacific), and are to be protected from significant adverse impacts (FAO, 2009b). The ISA recognizes VMEs and has regulations in place to prevent serious harm to them (ISA, 2013b). In addition, the ISA has designated large sections in the Clarion–Clipperton Fracture Zone polymetallic nodule province as areas of particular environmental interest (APEIs) (ISA, 2011; Wedding et al., 2013), but has not yet done so for other mineral resources. There is no standard protocol for identifying VMEs or APEIs; the definition for VMEs is broad but includes criteria such as uniqueness or rarity, functional significance of the habitat, fragility, life-history traits of component species that make recovery difficult, and structural complexity (FAO, 2009a; Auster et al., 2011). ES can serve as one standard for designation. For example, it may be possible to discern areas of high aggregate ES value and identify them as VMEs when that value is above a specified level.

The United Nations Convention on Biological Diversity (CBD) has its own form of spatial protection called ecological or biologically significant area (EBSAs), which are defined as “geographically or oceanographically discrete areas that provide important services to one or more species/populations of an ecosystem or to the ecosystem as a whole” (CBD, 2008). EBSAs must meet the following criteria: uniqueness or rarity, requirement for survival, endangered or threatened species occurrence, vulnerability, fragility, productivity, diversity, and naturalness (CBD, 2008). The CBD has identified hydrothermal vents and seamounts throughout the global ocean as EBSAs (e.g. Juan de Fuca and Guaymas Basin hydrothermal vents, Atlantis seamount in the Indian Ocean), and indicates they should be managed in a way that conserves their integrity, which includes creating MPAs recognized by international law (CBD, 2008).

Within ISA mining claims, there are also other potential protections that can be allocated to maintain ES. These may include unmined reference sites, voluntary permanent or temporary unmined areas, or areas turned back to the ISA after prospecting or exploring. Protected areas should be sites that would have otherwise been mined in order to be effective and of value. One criterion for identifying protected sites could be the potential to replace or provide similar ES as those lost or damaged at the mined site.

The supply and demand of ES and their value can also be mapped spatially, providing a useful tool for marine spatial planning (Naidoo et al., 2008; Burkhard et al., 2012). Areas of high ES value should be considered for protections against mining-related activities that may decrease that value, with close attention to where the value would be lost and where the beneficiaries are. A map of ES demand can be used to facilitate equitable distribution of natural capital as the common heritage of mankind.

4.5.3.2. Thresholds and triggers. Accurate baseline data and monitoring during the exploratory phase may allow for the identification of environmental thresholds or triggers. An ecological threshold is a “tipping point” at which ecosystem conditions undergo a rapid and possibly irreversible change exceeding normal ranges (Groffman et al., 2006). If we know a threshold will be reached due to mining impacts in a given area, then that area may require spatial protections. Once mining begins, small losses of ES may be acceptable, but there may be thresholds or triggers that would require cessation of activity. The concept of a threshold can also be applied to ES as the point at which ES are no longer provided on a significant scale (Koch et al., 2009). Often services do not accrue or decline linearly (Barbier et al., 2008). This might come from unexpected impacts to ES, such as the cumulative effects of DSM and climate change. Identifying thresholds requires an established baseline and knowledge about natural variability and, therefore, may prove especially difficult in the deep sea where there is a lack of data. Identifying ES thresholds may involve percentage losses of foundation species, such as those with chemosynthetic symbionts, or of habitat known to support a commercially-fished population. Another example could be a sediment plume that extends above a certain water depth that may disrupt shallow-water and vertically-migrating communities.

4.5.4. *Environmental damage compensation regime*

ES can play a role in the development of a DSM environmental damage compensation regime. Current ISA exploration regulations make DSM concession holders liable for any damage to the marine environment from their activities and require them to maintain proper insurance (ISA, 2010a, 2010b, 2010c). There is discussion of an environmental liability trust fund as well as a seabed sustainability fund which would fund research on best environmental practices and the effects of seabed dredging (ISA, 2015, 2016). However, these are not yet developed.

In terrestrial mining, firms are responsible for the release of any hazardous substances into the environment. For example, the U.S. Superfund, or Comprehensive Environmental Response, Compensation and Liability Act of 1908 (CERCLA), gives federal land managers the authority to demand response and cleanup funds for contaminated mining sites (Seymour, 2004). Superfund sites are generally waste sites that pose a risk to human and environmental health. ES are not specifically mentioned in the terrestrial mining legislation but they have increasingly been the focus of restoration efforts. The U.S. has a program called the Oil Spill Liability Trust Fund, which is funded by petroleum taxes, environmental fines, and compensation for damage to natural resources (26 U.S. Code §

9505). The fund is used to quickly respond to accidents and emergencies (Continental Shelf Associates, Inc., 2006), although it is not always sufficient for very large injuries (e.g. Deepwater Horizon).

The ISA is an international body with little power or capacity to tax its member states. However, there is discussion of royalty payments to the ISA (and how they may change over time in response to increasing concession holders, decreasing costs, or other economic factors) as contribution to the common heritage of mankind. Seabed minerals found in international waters are considered the "common heritage of mankind" (UNCLOS, 1982). ES related to the same waters should be treated similarly because they can provide benefits to society as a whole. Known short- and long-term damages to and loss of ES caused by DSM should be internalized in order to reflect the total social cost of DSM. In order to set an effective environmental damage compensation regime, the lost economic value associated with diminished ES requires reasonably accurate quantification. The incorporation of ES into baseline data collection, pilot mining tests, and monitoring programs can help calculate the value of lost environmental benefits and that value can be used to create an efficient compensation regime.

The revenue raised from compensation for lost ES and environmental damage can be used to compensate stakeholders (once identified) including the general public, to fund the creation and enforcement of MPAs, to restore impacted sites (if and where possible), or for scientific research that improves environmental management of the deep-sea environments being altered. The draft ISA regulation for commercial DSM includes a sustainability fund to direct further research and develop technology (ISA, 2016). It could be financed with environmental damage compensation payments and with any patent royalties from previously funded research.

5. Knowledge gaps relevant to identification and quantification of ecosystem services and potential tools to fill them

5.1. Linkages between structure, function, and service

ES are provided by ecological functions (supporting services) that are supported by ecosystem structure (Fig. 1; Table 1) (Kremen, 2005; Barbier et al., 2011; Thurber et al., 2014). Knowledge of the linkages among structure, function, and service are essential to predicting DSM impacts and calculating losses in ES and their value. In order to quantify and valuate ES, the mechanisms by which they are provided must be known. This could include fluxes of nutrients, metabolic rates, behavior, natural variability, and drivers of change.

Perhaps the biggest anticipated impact of DSM on the marine environment is loss of biodiversity. Biodiversity has been shown to increase function in the deep sea (Danovaro et al., 2008), and therefore, a loss of biodiversity can potentially result in the loss of ES. The ISA requires DSM concession holders to collect baseline data and monitor any DSM impacts on the marine environment (ISA, 2010a, 2010b, 2010c). Representative fauna and dominant species of all size classes from a variety of habitats, including the water column, are required for such an assessment and must be sufficient to characterize the biodiversity of deep-sea habitats. However, maximizing biodiversity is not the same as maximizing ES or function. There are often tradeoffs between biodiversity and ES. In wetlands for example, there are nonlinear relationships between species richness and primary productivity, and consequently carbon sequestration (Barbier et al., 2008; Naidoo et al., 2008; Bene et al., 2011). The contribution of biodiversity to ecological function (supporting services) and provision of services is still largely unknown in deep-sea systems. Without further knowledge regarding these relationships, it remains difficult to translate these recommended measurements into achievement of better ecosystem health.

The concept of ES is rooted in terrestrial systems. The deep sea, in contrast, tends to have less clearly defined boundaries and may need novel approaches in order to understand and implement deep-sea ES as a guiding framework (Jobstvogt et al., 2014a). Next-generation genetic tools (e.g. next-generation sequencing, use of environmental DNA) can potentially provide a more complete picture of deep-sea biodiversity and also inform on its contribution to ES, particularly in regards to microbial nitrogen cycling, carbon fixation, and other regulating services (Baker et al., 2013; Gibson et al., 2015). Transcriptomics, proteomics, and metabolomics can identify biochemical pathways that may reflect functions (supporting services) linked to global element cycling, or may illuminate novel attributes that can lead to industrial applications (Skropeta and Wei, 2014). Although it can be difficult to interpret data generated from genetic tools due to lack of knowledge, their use may identify dominant taxa (e.g. Dell'Anno et al., 2015) that are important to ES. Biological traits analysis is another tool that can potentially reveal linkages among structure, function, and ES, transcending taxonomic differences among regions or ecosystems. This method statistically analyzes the relationship between multiple biological traits and environmental processes or parameters (Bremner et al., 2006). For example, the abundance of burrowing fauna can influence a benthic system's capacity to transport and store organic matter, nutrients, and contaminants (Constable, 1999; Reise, 2002). Application to the deep sea may prove challenging due to the lack of data on life histories (e.g. reproductive mode, larval survival rates) and behavior (e.g. feeding mode, vertical or horizontal migration). However, as more data are collected, biological traits can provide insight into environmental variability and function indicators, and more effective marine protected area designation (Frid et al., 2008; Mitwally and Fleeger, 2016).

5.2. Life histories, ranges, and genetic connectivity

Information about key species associated with ES is crucial to identifying ES and minimizing DSM impacts on them. For example, in Namibia mining impacts in phosphorite beds may remove ecosystem engineers (e.g. sponges, sea pens) or degrade nursery habitat for commercially-fished species (e.g. monkfish, hake, or their forage species, the bearded goby), resulting in decreases in fisheries landings. New research is needed to examine life histories of key species, including geographic dispersal, range, and ontogenetic changes in habitat to illuminate the linkages necessary for the provision of ES. Genetic connectivity among habitats must also be researched for insight into potential recovery times or probability of extinction. Areas with higher genetic connectivity may recover their biological communities more quickly. Patterns of gene flow and connectivity can also be helpful tools in designating "set-asides" (protected areas that support biodiversity and connectivity lost at the mining site) and unmined reference sites (Boschen et al., 2016).

New technology and instruments, such as the SentrY Precision Robotic Impeller Driven sampler (Billings et al., in press), can increase sampling capacity over larger spatial scales, longer time periods, and more types of samples (i.e. larvae). These sampling capabilities can lead to insight into larval dispersal, species ranges, and habitat-specificity of different life stages in the deep sea. The use of autonomous and remotely-operated vehicles is also helpful to better understand deep-sea processes. In particular, high-definition pictures and videos allow for visual surveys and observations that can help identify ES. The actual visualization of deep habitats may reduce current sampling biases by allowing scientists to observe organisms, like mobile fish, that can avoid capture.

5.3. *Spatial and temporal scales*

Deep-sea ecological functions (supporting services) and the ES they support operate over a large range of spatial and temporal scales. Data collection and monitoring must reflect function-specific scales in order to accurately evaluate them. Furthermore, assessments must account for potential synergies among deep-sea functions. Interactions among functions are difficult to study when there is still an incomplete understanding of the deep sea and its habitats. For accurate ES assessment, new studies are needed addressing how deep-sea habitats change over space and time, and their interactions with the ecosystems of the surrounding seafloor and overlying water column, and with global geochemical cycles (Levin et al., 2016).

5.4. *Recovery of structure, functions, and services*

Deep-sea ES are dependent on ecological functions (supporting services) that will be affected by DSM (Glover and Smith, 2003; Clark et al. 2010; Van Dover, 2010). Research is needed under realistic conditions to determine whether biological communities will be able to recover from these impacts and, if possible, the time it would take to return original ES (Van Dover et al., 2014a). Resilience measures, such as recovery rates and thresholds (Mumby et al., 2014) that are sensitive to both spatial and temporal scales of the DSM activity and its impacts, need to be developed. This information is what participants in a contingent valuation survey will need to know in order to make an informed decision (Mitchell and Carson, 1989). Thresholds that are impossible to reverse may be reached. Rather than discover these thresholds after the fact, there is an opportunity to identify them before the start of DSM.

5.5. *Economic valuation of ES*

ES provide a tool that links ecosystems with human well-being, which then allows for economic valuation of these benefits. However, valuation has proven difficult to do accurately in the deep sea due to the lack of an adequate information base (Wattage et al., 2011; Jobstvogt et al., 2014a, 2014b). As a result, the data collection required by concession holders is essential to better understanding deep-sea ES. Habitat-specific measurements should also be included to monitor unique characteristics (e.g. sulfur recycling at hydrothermal vents). The data required to put values on ES not only include magnitudes (including how they vary over time and space), but also measurements of how ES are used by people and their perceptions of what the deep sea contributes to their well-being. Using an ES approach requires interdisciplinary collaboration between the natural and social sciences that may result in novel approaches and techniques in order to accurately quantify and value ES.

5.6. *Definitions of terms*

ISA regulation must be consistent with the principles set forth by UNCLOS (e.g. seabed minerals found in international waters must be treated as the “common heritage of mankind”), but interpretation and definition of terms remains a challenge. Current exploration regulation states that the ISA cannot approve any activities that might pose “serious harm” or “significant adverse change” to the marine environment (ISA, 2010a, 2010b, 2010c). However, the definitions of “serious harm” and “significant adverse change” are still points of debate. ES can serve as one measure for identifying serious harm, e.g., if an activity will result in the loss of ES sufficient to affect mining decisions. The definitions of these terms are likely dependent on how a healthy deep-sea habitat is defined and exactly what it is we want to protect (e.g. biodiversity).

Similarly, existing exploratory regulation calls for a precautionary approach (Rio Declaration, 1992), but how to operationalize such an approach is still ambiguous. Under the National Environmental Policy Act in the U.S., the Council on Environmental Quality has created a mitigation hierarchy: avoid, minimize, rehabilitate, and offset (CEQ, 2005). We recommend that these activities directly incorporate ES. While monitoring ES and mitigating for adverse impacts to them may help, practical implementation is likely to be complicated. The potential for rehabilitation and restoration in the deep sea is unknown (Schriever et al., 1997; Van Dover et al., 2012), but offsets are a major topic of current discussion. ES offsets should at the very least replace the same ES, provide a similar magnitude of benefit in as close geospatial proximity as possible, and serve the same stakeholders.

6. Conclusion

Incorporation of ES into international DSM regulation is a reasonable goal that will foster sustainability objectives. There is a single regulatory agency to consult (the ISA), commercial mining has yet to occur so there is an opportunity to set desirable precedents, and the quantification of ES will greatly facilitate the operationalization of a compensation regime that provides payment for environmental harm. Within national jurisdictions, the challenges may be greater as there are at least 150 nations with deep seabed and deep resources. For all, challenges to adopting an ES framework include the development of new knowledge needed to accurately quantify and valuate ES, and of optimal indicators of ES. New technologies and techniques, such as next-generation genetic tools, biological traits analysis, and novel robotic sensors can potentially help address these challenges. Illuminating the linkages among physical, chemical, and biological structure, ecological function (supporting services), and ES in those deep-sea settings subject to mining impact is a nascent but important topic of research for the future.

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