Environmental considerations for impact and preservation reference zones for deep-sea polymetallic nodule mining

Highlights

- Two types of environmental monitoring zones are required per deep-sea mining claim
- 11 recommendations are presented for establishing these reference zones
- Effective monitoring programmes require robust statistical design of zones
- To determine statistical power, comprehensive baseline surveys are required
- Zones should be sufficient to allow assessment of a range of impacts in all affected habitats

Keywords

Spatial management; resource extraction; anthropogenic impact; monitoring; seafloor minerals; environmental management

1 Introduction

Deep-sea mining activities are being proposed in national and international waters, focusing on three main resource types: polymetallic nodules (nodules), seafloor massive sulphides (SMS) and cobalt-rich crusts (crusts). Mining interest for nodules is mostly centred in the Clarion Clipperton Zone (CCZ) of the northern equatorial Pacific, SMS on active plate boundaries, and crust mining on seamounts, principally in the northwest Pacific. Whilst these three types of minerals will each require bespoke technology and approaches (Table 1), they share in common the potential to cause serious harm to the marine environment [1]. In the case of nodule mining, the footprint will be large, on the scale of hundreds of square kilometres of seafloor each year [2, 3]. The spatial footprint of SMS and crust mining will be smaller but still ecologically significant [4]. Seabed mining activities for different mineral resources at shallower depths will not be covered here, but it is worth noting that some large operations exist (e.g. diamond sand mining in Namibia). Within national jurisdiction, some deep-sea SMS mining operations have been approved to date including in Papua New Guinea [5] and in Japan [6], though they have not yet gone into commercial production. No deep-seabed mining (DSM) in the legal “Area” beyond national jurisdiction has yet been approved, and the environmental regulations and approval process for commercial DSM exploitation are still under development by the International Seabed Authority (ISA). The detailed requirements for environmental monitoring of commercial DSM are likewise still in development.

The mining of deep-ocean minerals, like any form of human development, will impact the surrounding environment and biological communities. The mining vehicle is likely to disturb the sediment in wide tracks [7], which will likely remove most organisms. Noise and light pollution from the mining machinery and support vessels will impact biological communities from the sea surface to the deep-ocean floor [8]. Sediment plumes created by the seabed mining operation will spread in the water column and eventually settle on the seafloor, smothering any fauna in both the directly disturbed area and surroundings [2]. Sediment plumes may also arise from the surface de-watering operation and will likely be discharged at depth [9]. Models suggest that large sediment plumes will be created that spread over extensive areas, particularly in the case of nodule mining on finegrained abyssal sediments [10]. It is estimated that the sediment plume will cover at least twice the area of the operation [11].

As an input to the ongoing development of ISA environmental rules and regulations, this paper outlines key considerations relevant to the design and selection of sites to monitor impacts of DSM. Although many of these considerations will be of relevance to all types of seabed mining, here we focus on polymetallic nodule mining. Though good design principles remain relevant regardless of the effect being measured, not all possible effects are considered here (e.g. impacts from noise). This paper takes into account existing ISA guidance, where available, as well as some of the issues raised during workshops in 2015, 2016 and 2017 (see acknowledgments). For the purposes of this paper, environmental management of DSM shall be understood to be a mechanism to minimise direct and indirect damage of mining-related activities to the marine organisms, habitat, and ecology of the region. To achieve these ends (see Table 2), it is necessary to avoid / minimise the negative impacts where possible, which in turn requires a level of monitoring such that impacts are readily detectable and assessable, before they cause serious harm. For those places where impacts have occurred, physical, biological and ecological recovery will also need to be monitored. Establishing an effective monitoring regime requires understanding the distribution of the parameters of interest in a region before mining commences, and hence detailed baseline surveys of the mining areas are first needed, before the monitoring and mitigation plans can be developed.

The underlying concepts for spatial management zones are similar for all types of mining. However, there are differences in considerations concerning the scale, spatial constraints, and ecology of these areas (Table 1). The biological communities associated with active SMS deposits, for example, are very different from those in nodule fields, with the former being isolated areas with relatively high densities of fauna but relatively low diversities [12], whilst the latter are the opposite [13]. Crusts and inactive SMS deposits are associated with typically diverse communities particularly of sessile suspension feeders [14], and unlike the other DSM resources, crusts may also be associated with commercial fish species [1]. As a result of these and other critical differences, design of the monitoring regimes for each of the DSM resource types will necessarily differ in many aspects (Table 1). We focus here on polymetallic nodule deposits. However, many of the underlying design criteria which shape decisions on monitoring, as discussed below, will be similar across all deposits.

TABLE 1 HERE

TABLE 2 HERE

2 Interpretation of existing guidance on claim-scale spatial management areas

The legal and regulatory requirements for environmental monitoring of deep-sea mining will likely be the most important factor controlling what is done. The ISA provides some information on spatial management at two scales: at the scale of individual mining claims and at a regional scale. A regional environmental management plan has been developed for the CCZ [15], which sets out a range of representative areas for the region to be protected from mining activities (known as ‘areas of particular environmental interest’, APEIs). The APEIs are important to regional-scale management [16] but are not necessarily part of the claim-scale monitoring scheme and so are not covered in detail here. The ISA does provide guidance on claim-scale spatial management for all types of mining in the current “mining code” [17, 18], which provide an important approach for addressing several key monitoring objectives (Table 2). In this context, the term “mining code” refers to the collection of rules, regulations and guidance concerning DSM. The mining code currently applies only to exploration activities, and sets out two types of spatial environmental management zones (subsequently referred to as ‘zones’) within the mining claim area for assessing mining activities: impact reference zones (IRZ) and preservation reference zones (PRZ). These are defined as follows:

IRZ are areas to be used for assessing the effect of each contractor’s activities in the Area on the marine environment and which are representative of the environmental characteristics of the Area.

PRZ means areas in which no mining shall occur to ensure representative and stable biota of the seabed in order to assess any changes in the flora and fauna of the marine environment.

The draft exploitation code [19] and environmental regulations [20] do not yet provide guidance for the implementation of PRZ or IRZ. The environmental management plan for the CCZ [15] provides some additional information (ISBA/17/LTC/WP.1 section VII.B.46.c and d):

Contractors will provide in their environmental management plans the designation of the required impact and preservation reference zones for the primary purposes of ensuring preservation and facilitating monitoring of biological communities impacted by mining activities.

Impact reference zones should be designated to be within the seabed claim area actually mined.

Preservation reference zones should be designated to include some occurrence of polymetallic nodules in order to be as ecologically similar as possible to the impact zone, and to be removed from potential mining impacts;

Contractors are required to minimize potential impacts on established preservation zones, and the Authority should consider the potential for impact on established preservation zones in evaluating any application for a mining licence

Figure 1 provides a plausible graphical representation of these zones within a nodule mining claim. The PRZ is principally a ‘control’ site for the IRZs, which measure impacts. However, being located closer to the claim area than the APEIs, the PRZs could also play important roles for conservation, for example providing connectivity as ‘stepping stones’ and sources for recolonization for impacted sites. However, to fulfil a conservation objective the PRZ would need to be in place for the long term and not mined. In both conservation and monitoring roles, PRZs will need to be representative of mined habitats and protected from the primary and secondary effects of mining activities. However, their contribution towards meeting conservation objectives, as part of a potential representative network of protected areas, is not the focus of this paper (see box 1), which looks at monitoring.

FIGURE 1 HERE

BOX 1 HERE

3 Recommendations for claim-scale spatial management

There are many practical problems in the detection of anthropogenic impacts on biological communities [21], particularly in the deep sea. Furthermore, deep-sea environments associated with DSM differ from shallower habitats in several important ways, which affect both statistical confidence and power, and will vary by resource type (Table 1). Many communities have large natural temporal variances in the populations of many species [22]. These populations often show a marked lack of concordance in their temporal trajectories from one species and one place to another [21, 23]. This problem is further exacerbated in many deep-sea areas by low densities of fauna and high diversities [24-26], although this may not be the case in active venting systems [12] or seamounts [27]. Sampling must therefore be of sufficient size and replication to identify unusual patterns of change in suites of interacting and variable measurements often spanning considerable distances [21, 28]. Furthermore, the first monitoring samples should be completed prior to mining starting to provide an appropriate baseline. When these factors are taken into account and applied to mining a range of considerations become apparent, which are explored below and summarised in Figure 2.

FIGURE 2 HERE

3.1 Zone size

Size is a fundamental characteristic of spatial management zones. Conservation considerations aside, zones need to be sufficiently large to contain a representative subset of organisms sufficient for a statistically robust assessment of ecosystem integrity. Robust assessment of biological assemblages requires enumeration of hundreds of individuals from as many species as possible [29]. Additionally, sites will need to be large enough to allow regular and repeated destructive sampling (e.g. box cores, trawls, and epibenthic sleds [30]) over a long period, likely decades, without any impact from sampling being detected. Densities of some organisms, particularly larger-sized animals (megafauna), are very low, especially in nodule areas. In the case of megafauna in nodule fields especially, representative sampling may require (photo / video) assessment of transects kilometres in length [31]. Depending on the effect size being measured, the variances of the indicator under investigation and the statistical power desired, anywhere from 25 to >100 replicates may be necessary [32]. These will need to be contained within the zone(s).

In line with the precautionary approach [33] it will be necessary to design zones based on precautionary assumptions. While default minimum sizes of protected areas are typically specified by the regulator, other more flexible science-based approaches for determining appropriate size could be taken, assuming the capacity exists to assemble the relevant local data and to assess local populations and their reproductive potential. While science-based local assessments increase the likelihood of effectiveness [34], they do come with greater research costs. Thus, a management system could begin with a precautionary (i.e. likely too large) size of a PRZ as a default position, which could be modified (e.g. reduced in size) as more data become available suggesting what minimum dimensions might be required to achieve the objectives of viability, representability and resilience to sampling impact.

Finally, given the expected long duration of the monitoring (at least over the life of a 20 or 30-year contract, if not longer), PRZs will need to be large enough to self-support populations of the species being monitored. Otherwise, reductions in the populations of species in the PRZ (which is providing a representation of the natural environment not impacted by mining) because of insufficient recruitment could be confused with natural declines in the region that were caused by other factors, such as climate change.

3.2 Separation of zones

Spatial management zones will need to have sufficient geographical distance from mining to ensure that the PRZs are not impacted by mining activities, and the IRZs are affected by a meaningful range of affects. However, environmental heterogeneity tends to increase with spatial scale [35], so zones closer together are likely to be more representative of each other. Thus, both types of zones will need to be close enough to each other and to the mining activities to ensure that they represent reasonable examples of impact and control treatments. Given the currently unknown behaviour of mining plumes, the question of appropriate spacing is particularly difficult, and will therefore require taking an adaptive approach for each of the resource types, to measure the varying impacts of the plumes over distance, and to control for them. It may be necessary to place IRZ at multiple distances away from the mining impact to evaluate the gradient of disturbance and its impacts.

3.3 Statistically robust monitoring

The monitoring design and schedule should be able to reliably detect the impacts of ongoing mining activities by comparing the state of the ecosystem subjected to mining with the state of the ecosystem that would have existed if mining had never occurred. This requires an approach that can reliably estimate the effect of mining activities amid the diverse sources of spatial and temporal variability in the deep sea, which in turn requires data to be collected before the mining has occurred [36, 37], during, and at multiple points after the mining [28]. Spatiotemporal variation (i.e., unique spatial and temporal fluctuations at each site) is addressed, in part, by repeated sampling through time [28] and at multiple sites [21] (see below). Many impacts will lead to step-changes in the ecosystem after mining, which are easier to detect [38]. However, some impacts from mining, particularly secondary impacts (such as from plumes), may not cause immediate or constant changes to a system. Indeed, complex ecological interactions may take time to propagate through the system, leading to time-dependent effects of disturbance [28]. Monitoring needs to be able to detect these changes. It should also be able to detect combined or cumulative effects of other environmental changes and attribute these to a cause or causes. Regular monitoring is also important to provide the information necessary for responsive adaptive management [39].

A statistically robust sampling programme should be implemented to consider the points raised here [e.g. 40]. The robustness of the plan should be tested and scrutinised prior to sampling by statistical experts familiar with working in the deep sea. Baseline data collected at the claim sites should be sufficient to allow for estimations of population means and variance in the indicator of interest (e.g. species richness) required for a formal power analysis of a sampling plan. Three variables are of relevance here: significance (the error rate that you are willing to accept), power (the probability that the sampling plan will find a statistically significant difference in the indicator between the IRZ and PRZ when there is a difference), and effect size (the size of the difference in the indicator between the PRZ and IRZ). Typically, a significance level of 5% and a power of 80% are selected, but arbitrary convention may not be appropriate for some questions. Measuring smaller effect sizes will require more replicates than larger ones, and hence choosing an appropriate value beforehand is necessary. There are few conventions concerning effect levels to be measured, and will indeed be heavily dependent on the particular indicator. However, effect levels greater than one standard deviation (a change of ~68% of the measured value, if normally distributed data) are likely to already fall within the legal realm of 'serious harm' to the environment. Thus, it is expected that measuring an effect level less than one standard deviation (e.g. 0.5) will be necessary, where an effect size of 0.5 is that the mean value of the indicator in the PRZ is 0.5 standard deviations smaller (or larger) than that in the IRZ.

Given the multiple considerations and complexities involved, a system of peer-review or independent verification of sampling designs would help ensure that the design was robust prior to commencement of an expensive sampling programme. Marine data acquisition in other industries, such as oil and gas, has generally become formulaic and focused on the known impacts and effects of those industries, in part to meet existing legal and commercial drivers [41]. In moving into the deep sea environment this approach has revealed problems in terms of robustness of data for understanding impacts to deep-sea ecosystems [41]. As a result, it will be insufficient to solely rely on shallower water protocols; rather, these will need to be revised for the deep-sea to provide the necessary statistical power for measuring the relevant deep-sea ecological indicators.

3.4 Replication of zones

Monitoring multiple examples of each type of zone enhances the statistical power to detect effects, and thus in the deep-sea where statistical power is usually an issue, it should be assumed that multiple replicates of PRZs and IRZs will need to be established. The comparison between a single impact and a single control location is confounded by any non-mining-related temporal ecological variation. For example, populations often have different temporal trajectories in different locations, and temporal interaction among places is also common [21]. Multiple control sites are also necessary to detect disturbances that do not affect long-term mean abundances of a population, but, instead, alter the temporal pattern of variance of abundance [42].

To be effective, the location of zones should be defined as soon as possible in the mining process, at least in the preparation of the environmental impact assessment [43], but preferably in the initial planning stages [44]. However, at the start of a mining project there will be some uncertainty in the exact spatial and temporal pattern of mining activities. This may lead to inappropriate zones being defined, for example if IRZs are unsuited to mining, or mine plans change around designated zones. Furthermore, it is likely that some areas defined as PRZs or IRZs may turn out, after further monitoring, to be unrepresentative. Also, some PRZs may turn out to be too close to mining activities and will become impacted. These could be re-designated as IRZs; others may have to be retired. These changes in status of designated areas could be particularly significant, both scientifically and economically, if unreplicated PRZs are impacted, as that this could require operational modifications or reductions in the planned mining area or movement of mining into less valuable resource areas. Finally, natural small-scale episodic events may occur in some areas reducing their value for monitoring, particularly in the case of highly dynamic SMS vent ecosystems. For all these reasons, increasing redundancy through designation of multiple sites is strongly suggested in order to mitigate a range of potential problems and allow for flexibility and adaptability in both the contractor's mining activities and the monitoring plan.

3.5 PRZs and representativity

Recent research [25, 26] illustrates the importance of nodules for abyssal biodiversity. Likewise, the minable resource may also be important for biodiversity associated with SMS [4] and crust deposits [14]. Ecological communities likely also respond to finer-scale environmental variation, such as variation in local geomorphology [25]. Consequently, to fulfil the obligation of representativeness of the PRZ it will be necessary to demonstrate that the PRZs contain similar ecological and geomorphic features as the planned mining area, which in the case of nodule mining will mean a similar density and size of nodules. Thus, "including some occurrence of polymetallic nodules" [15] is likely an insufficient criterion for a PRZ, which is "to be as ecologically similar as possible to the impact zone" [15]. Consideration should also be given to PRZs having other environmental traits that are the same as those sites suitable for mining, as these traits may also affect ecological community structure. For example, having limited slope and rugosity in the case of nodule mining, particularly as variation in seabed structure is known to affect communities in abyssal plains [45]. Once suitable areas have been identified, the IRZs and PRZs should be selected at random within those areas for each habitat type (i.e. stratified random sampling) [46].

3.6 Preservation reference zones for other habitats

Outside of the mined habitats, it is likely that other habitats, including ecologically or biologically significant areas may exist within the claim zones and that these may be impacted from mining activities through plume and other effects. These habitats could, for example, include areas unsuitable for mining because of geomorphological features (e.g. seamounts in a nodule mining area) or lack of resource (e.g. nodule free areas), and areas with significant aggregations of habitat-forming organisms (e.g. cold-water coral reefs near SMS deposits). To understand the full impacts of mining, it will be necessary to identify these ecologically important areas prior to mining and also include them in any monitoring programme. In addition, as discussed above, it will be necessary for statistical purposes to ensure that representative portions of all local habitats are spared from mining impacts. These may require an additional sub-class of PRZs to be recognised for each special feature and habitat type.

3.7 Consideration of the effects of plumes

Sediment and chemical plumes from mining disturbance are likely to be an important impact from DSM with potentially far-reaching [10, 47, 48] and damaging impacts [49, 50] with expected negative consequences to both benthic and pelagic deep-water communities. The geographic location of plume impacts will almost certainly include the mined area, but may extend to be several times the spatial extent of the mining activities themselves [10, 51]. Sediment plumes may also fall onto future mining blocks, where they will later become re-suspended and re-distributed further, thus amplifying their impacts.

The impact of plumes from DSM activities is poorly known, despite several experiments designed to simulate them [52-55]. Environmental management of current and future activities will require that impacts from plumes are measured and understood. Thus, some impact reference zones will need to be designed specifically for the effects of plumes. Here, to differentiate these from other IRZs, we add a ‘P’ to the designation IRZ-P. IRZ-Ps would be situated in an area that is representative of the mined area that is not mined but is expected to receive significant impacts from the sediment plume. A gradient of plume-related impacts (e.g. settled sediment thickness) will need to be evaluated.

It will be necessary, but could prove to be difficult, for the contractor to provide evidence that the designated PRZs are not affected by the impacts of plumes and sediment deposition, bearing in mind that sub-lethal long-term effects of low levels of increased sedimentation are currently unknown. If a PRZ is found to be impacted, it will no longer be able to fulfil its role as defined in the mining code of being able to detect changes in the mined area (though it could become an IRZ-P). Initial modelling results [10] suggest that plume impacts will extend over areas several times larger than the mined area, particularly if the locations of low levels of additional suspended materials are assessed.

Whilst the direct impacts of mining are difficult to mitigate (avoidance: mine or don’t mine), the secondary impacts caused by plumes, noise, etc., are mitigatable and should be the focus of management measures to minimise such disturbance. The spatial distribution of plume impacts is a function of four components: i) engineering: the type of mining machinery in use – how deeply it digs, how finely (if) it grinds up the raw ore, how it moves along the seabed, and how it discharges its “exhaust” of unwanted sediments (both in the deep-seafloor operations and on the surface discharge of additional water and fine particulate); ii) geology: the quantity and nature of the ore, as well as the associated seabed sediments, how long they stay in suspension and the amount of dissolution of elements; iii) hydrography: the strength, direction, and variability of local eddies and currents at the time of mining [56]; and, iv) the duration of the mining activities. To effectively predict the spatial extent of the plume and hence set effective spatial management zones, models that use realistic data for all four components will be necessary. Likewise, mitigation measures to keep the extent of plumes to minimum could focus on these four components, exploring engineering solutions in concert with geological and hydrological site selection criteria, where they are least likely to have lasting impacts.

Research is required to determine the levels of suspended sediment or chemical concentrations that are not acceptable in a PRZ (based on smothering or toxicity). This will likely be set at a threshold where either sediment cannot be detected or where it has been shown to have negligible effects on deep-water organisms. This threshold could also be used for monitoring and enforcement, but may take several years of careful monitoring to establish. In the meantime, a precautionary value will need to be selected.

3.8 Transboundary effects

It is very possible that some of the impacts of mining will extend beyond the boundaries of the contractual / license area, particularly the impacts of plumes. This would require monitoring outside of what a contractor may be willing, obliged or allowed to provide. Alternatively, it could mean that the contractor could not mine up to the boundary of their area. These concerns are particularly relevant to mining activities generating large plumes, those at the edge of claim zones, and in small sized or irregularly shaped claims with a greater edge-to-area ratio and hence increased chances of edge-related effects spilling over into neighbouring areas. The likelihood of these concerns are increased if contractors give up parts of their exploration area when they move to exploitation. If it should happen that these impacts extended to a neighbouring contractual / license area held by another State Party, they may present diplomatic as well as liability challenges. Likewise, if plumes were to fall onto unclaimed areas there could be questions both concerning the liability and also who would pay to monitor these areas. Finally, plumes that fell within national jurisdiction would likely trigger environmental liability based on existing international environmental jurisprudence [e.g. 57], which again would need to be expanded to take into account the unique legal specifics of DSM. In all cases, to determine the legal ramifications, having a robust monitoring programme in place will be necessary to: i) detect such trans-boundary effects as they occur, and ii) to determine if these effects are likely to cause serious harm to the environment. The first point suggests that monitoring outside of claim blocks will be necessary when spillover is likely. The second point suggests that such monitoring would have to be factored in before mining commences; i.e. the appropriateness of trans-boundary monitoring should be a consideration in the monitoring plan from the outset.

3.9 Integration with other human activities

In an increasingly crowded ocean, the zoning of PRZs and IRZs will ultimately require integration into wider spatial planning and management. Maps and coordinates of zones should be made public (as has been the practice to date with the Pacific APEI). Additionally, they could be communicated to secretariats of other relevant international maritime bodies to better ensure they are taken into account. However, in cases where there are other potentially conflicting activities, it is unlikely that notification alone will be sufficient, and cooperative mechanisms will need to be developed (for example the International Cable Protection Committee and the International Maritime Organization) [58]. Additionally, the PRZs should be included in international databases of protected areas (e.g. IUCN Protected Planet, http://www.protectedplanet.net/) and take into consideration other international designations (e.g. UN General Assembly *vulnerable marine ecosystems*,).

3.10 Sharing PRZs

It is conceivable that contractors may want to share PRZs along a common boundary of their claim areas. This offers the possibilities of cost and effort savings as well as a way to carry out more intensive monitoring. Combining the financial resources for monitoring by two contractors may allow for the installation of ambitious and novel monitoring equipment, such as seafloor observatories [59]. Seafloor observatories could provide real-time data to enhance day-to-day environmental management, for example detecting peak current events, during which mining could be avoided because plumes generated would be widely dispersed. Combining PRZs also has the advantage of ensuring monitoring approaches are the same between two contractors, although coordination of monitoring activities around two independent mining developments may be difficult. A trans-boundary PRZ should be part of a wider array. Monitoring just one PRZ for two contract areas is not being suggested here, and would have several disadvantages: 1) it reduces replication, which would leave monitoring more vulnerable to the many possibilities of technical and ecological uncertainty; and, 2) it also reduces the overall spatial sampling carried out in the mining areas, with subsequent reductions in the amount of information available for the regulator for regional planning and understanding. Therefore, whilst cost-saving and cooperation among contractors should be encouraged, it should not be employed to replace rigorous sampling and replicates.

3.11 Verification of results

For mining using new and developing techniques, it should be advantageous for independent observers or verification agencies to be used to help ensure the independence and robustness of results. Transparency, particularly in the nascent stages of this new industry, will be important in developing shared good practices and building trust [60, 61]. Sampling plans would be made publicly available for external scrutiny, in addition to peer review, prior to sampling. Making subsequent data and metadata, analysis and interpretations publicly available will also help improve accountability and credibility of the results from this new and emerging industry.

3.12 A proposed three-step adaptive approach

When setting up a monitoring scheme for a given mining block within a contractual / lease area, three steps might be considered: 1) beginning with more PRZs than will ultimately be used in long-term monitoring to ensure statistical robustness as well as redundancy given various uncertainties; 2) re-designating some PRZs that are affected by mining into IRZs (while retiring others that are not helpful to the monitoring plan); and 3) learning from the current situation and the future plans for mining to set up a new array of PRZs/IRZs an appropriate time in advance (e.g. 3 years) in order to acquire the necessary baseline information. In this scheme, there would be three activities operating in parallel within a contractual area: i) active mining and monitoring; ii) baseline monitoring at the next block in anticipation of mining; and iii) surveying / selecting the subsequent mining block after the one currently being monitored for baseline information. Flexible iterative management, as suggested here, allows for learning and adapting through experience, and could prevent delays resulting from inadequate or unsuitable baseline or monitoring data, whilst providing the Contractor a stepwise investment strategy, rather than having to put in place a full monitoring system from the outset. However, such flexibility is only possible if the contractual / licensing scheme allows for regular review and revision of Plans of Work. The ISA contractual system currently in place for exploration has very limited flexibility of this sort, and Plans of Work for exploration have seldom been modified over the course of their 20-year life spans.

4 Conclusion

The latest draft of the exploitation regulations [19] proposes separate Environmental Regulations, which are not yet completed. The ISA (July 2016; ISBA/22/C/CRP.1) states that guidelines are needed for establishment of IRZ and PRZ, which will feed into the Environmental Regulations. Establishing scientifically realistic and effective guidelines for spatial management zones should in turn inform the development of effective rules and regulations. Using existing experimental design guidance as a starting point, this paper has added considerations particularly relevant (or unique) to the deep-sea and DSM, in order to formulate recommendations for establishment of PRZs and IRZs (Figure 2). Although focused on mining activities in areas beyond national jurisdiction, the recommendations presented here would be applicable and useful to the design of spatial environmental management zones in national waters. PRZ and IRZ in crust, SMS and pelagic environments present additional challenges to those presented here for nodule systems. Additional critical thinking in collaboration with a wide variety of experts is necessary for appropriate mechanisms for establishment to be developed.

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References

[1] L.A. Levin, K. Mengerink, K.M. Gjerde, A.A. Rowden, C.L. Van Dover, M.R. Clark, E. Ramirez-Llodra, B. Currie, C.R. Smith, K.N. Sato, N. Gallo, A.K. Sweetman, H. Lily, C.W. Armstrong, J. Brider, Defining “serious harm” to the marine environment in the context of deep-seabed mining, Marine Policy 74 (2016) 245-259.

[2] H.U. Oebius, H.J. Becker, S. Rolinski, J.A. Jankowski, Parametrization and evaluation of marine environmental impacts produced by deep-sea manganese nodule mining, Deep-Sea Res. Pt. II 48(17–18) (2001) 3453-3467.

[3] C.R. Smith, L.A. Levin, A. Koslow, P.A. Tyler, A.G. Glover, The near future of the deep seafloor ecosystems, in: N. Polunin (Ed.), Aquatic Ecosystems: Trends and Global Prospects, Cambridge University Press, Cambridge, 2008, pp. 334-349.

[4] R.E. Boschen, A.A. Rowden, M.R. Clark, J.P.A. Gardner, Mining of deep-sea seafloor massive sulfides: A review of the deposits, their benthic communities, impacts from mining, regulatory frameworks and management strategies, Ocean Coast. Manage. 84 (2013) 54-67.

[5] Nautilus Minerals, Environmental Impact Statement Solwara 1 Project, Coffey Natural Systems Pty Ltd, Brisbane, Australia, 2008.

[6] Kyodo, Japan successfully undertakes large-scale deep-sea mineral extraction, Japan Times, Tokyo, 2017.

[7] D.O.B. Jones, S. Kaiser, A.K. Sweetman, C.R. Smith, L. Menot, A. Vink, D. Trueblood, J. Greinert, D.S.M. Billett, P.M. Arbizu, T. Radziejewska, R. Singh, B. Ingole, T. Stratmann, E. Simon-Lledó, J.M. Durden, M.R. Clark, Biological responses to disturbance from simulated deep-sea polymetallic nodule mining, PLoS ONE 12(2) (2017) e0171750.

[8] C. Peng, X. Zhao, G. Liu, Noise in the Sea and Its Impacts on Marine Organisms, International Journal of Environmental Research and Public Health 12(10) (2015) 12304-12323.

[9] K.A. Miller, K.F. Thompson, P. Johnston, D. Santillo, An Overview of Seabed Mining Including the Current State of Development, Environmental Impacts, and Knowledge Gaps, Frontiers in Marine Science 4(418) (2018).

[10] D. Aleynik, M.E. Inall, A. Dale, A. Vink, Impact of remotely generated eddies on plume dispersion at abyssal mining sites in the Pacific, Scientific Reports 7(1) (2017) 16959.

[11] K.M. Gjerde, P. Weaver, D. Billett, G. Paterson, A. Colaco, A. Dale, J. Greinert, C. Hauton, F. Jansen, D. Jones, P.M. Arbizu, K. Murphy, A. Sweetman, Implications of MIDAS results for policy makers: recommendations for future regulations, Seascape Consultants, Romsey, 2016.

[12] C.L. Van Dover, The ecology of deep-sea hydrothermal vents, Princeton University Press, Princeton N. J., 2000.

[13] J.D. Witman, K. Roy, Marine Macroecology, University of Chicago Press, Chicago 2009.

[14] T.A. Schlacher, A.R. Baco, A.A. Rowden, T.D. O'Hara, M.R. Clark, C. Kelley, J.F. Dower, Seamount benthos in a cobalt-rich crust region of the central Pacific: conservation challenges for future seabed mining, Diversity and Distributions 20(5) (2014) 491-502.

[15] International Seabed Authority, Environmental Management Plan for the Clarion Clipperton Zone. ISBA/17/LTC/7, International Seabed Authority, Kingston, Jamaica, 2011.

[16] L.M. Wedding, A.M. Friedlander, J.N. Kittinger, L. Watling, S.D. Gaines, M. Bennett, S.M. Hardy, C.R. Smith, From principles to practice: a spatial approach to systematic conservation planning in the deep sea, Proceedings of the Royal Society B: Biological Sciences 280(1773) (2013) 20131684.

[17] International Seabed Authority, Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area. ISBA/6/A/18, International Seabed Authority, Kingston, Jamaica, 2000.

[18] International Seabed Authority, Decision of the Assembly of the International Seabed Authority relating to the Regulations on Prospecting and Exploration for Cobalt-rich Ferromanganese Crusts in the Area. ISBA/18/A/11, International Seabed Authority, Kingston, Jamaica, 2012.

[19] International Seabed Authority, Developing a regulatory framework for mineral exploitation in the Area, International Seabed Authority, Kingston, Jamaica, 2016.

[20] International Seabed Authority, A Discussion Paper on the development and drafting of Regulations on Exploitation for Mineral Resources in the Area (Environmental Matters), International Seabed Authority, Kingston, Jamaica, 2017.
[21] A.J. Underwood, On Beyond BACI - Sampling Designs That Might Reliably Detect Environmental Disturbances, Ecol. Appl. 4(1) (1994) 3-15.
[22] K.L. Smith, H.A. Ruhl, B.J. Bett, D.S.M. Billett, R.S. Lampitt, R.S. Kaufmann, Climate, carbon cycling, and deep-ocean ecosystems, Proc. Natl. Acad. Sci. U. S. A. 106(46) (2009) 19211-19218.
[23] A.J. Gooday, A response by benthic Foraminifera to the deposition of phytodetritus in the deep sea, Nature 332(6159) (1988) 70-73.
[24] A.G. Glover, C.R. Smith, G.L.J. Paterson, G.D.F. Wilson, L. Hawkins, M. Sheader, Polychaete species diversity in the central Pacific abyss: local and regional patterns, and relationships with productivity, Mar. Ecol. Prog. Ser. 240 (2002) 157-169.
[25] D.J. Amon, A.F. Ziegler, T.G. Dahlgren, A.G. Glover, A. Goineau, A.J. Gooday, H. Wiklund, C.R. Smith, Insights into the abundance and diversity of abyssal megafauna in a polymetallic-nodule region in the eastern Clarion-Clipperton Zone, Scientific Reports 6 (2016) 30492.
[26] A. Vanreusel, A. Hilario, P.A. Ribeiro, L. Menot, P.M. Arbizu, Threatened by mining, polymetallic nodules are required to preserve abyssal epifauna, Scientific Reports 6 (2016) 26808.
[27] M.R. Clark, A.A. Rowden, T. Schlacher, A. Williams, M. Consalvey, K.I. Stocks, A.D. Rogers, T.D. O'Hara, M. White, T.M. Shank, J.M. Hall-Spencer, The Ecology of Seamounts: Structure, Function, and Human Impacts, Annual Review of Marine Science2010, pp. 253-278.
[28] L. Thiault, L. Kernaléguen, C.W. Osenberg, J. Claudet, Progressive-Change BACIPS: a flexible approach for environmental impact assessment, Methods in Ecology and Evolution (2016) n/a-n/a.
[29] J.M. Durden, T. Schoening, F. Althaus, A. Friedman, R. Garcia, A. Glover, J. Greniert, N. Jacobsen Stout, D.O.B. Jones, A. Jordt-Sedlazeck, J.W. Kaeli, K. Koser, L. Kuhnz, D. Lindsay, K.J. Morris, T.W. Nattkemper, J. Osterloff, H.A. Ruhl, H. Singh, M. Tran, B.J. Bett, Perspectives in visual imaging for marine biology and ecology: from acquisition to understanding, Oceanogr. Mar. Biol. Annu. Rev. 54 (2016) 1-72.
[30] A. Eleftheriou, A.D. McIntyre, Methods for the Study of Marine Benthos, Blackwell Science London, 2013.
[31] K.J. Morris, B.J. Bett, J.M. Durden, V.A.I. Huvenne, R. Milligan, D.O.B. Jones, S. McPhail, K. Robert, D.M. Bailey, H.A. Ruhl, A new method for ecological surveying of the abyss using autonomous underwater vehicle photography, Limnology and Oceanography Methods 12 (2014) 795-809.
[32] L. Lan, Z. Lian, Application of statistical power analysis – How to determine the right sample size in human health, comfort and productivity research, Building and Environment 45(5) (2010) 1202-1213.
[33] A. Jaeckel, The precautionary approach and environmental impact assessment in the context of the ISA, Griffith Law School and International Seabed Authority Workshop on Environmental Assessment and Management for Exploitation of Minerals in the Area, Surfers' Paradise, Queensland, Australia, 2016.
[34] C.M. Roberts, J.P. Hawkins, J. Fletcher, S. Hands, K. Raab, S. Ward, Guidance on the size and spacing of Marine Protected Areas in England, Natural England Commissioned Report NECR037, Sheffield, UK, 2010.
[35] P. Chesson, Mechanisms of Maintenance of Species Diversity, Annu. Rev. Ecol. Syst. 31(1) (2000) 343-366.
[36] A. Stewart-Oaten, W.W. Murdoch, K.R. Parker, Environmental impact assessment: 'Pseudoreplication' in time?, Ecology 67 (1986) 929-940.
[37] C.W. Osenberg, R.J. Schmitt, S.J. Holbrook, K.E. Abu-Saba, A.R. Flegal, Detection of environmental impacts: natural variability, effect size, and power analysis., Ecol. Appl. 4 (1994) 16-30.

[38] A. Stewart-Oaten, J.R. Bence, Temporal and spatial variation in environmental impact assessment, Ecol. Monogr. 71(2) (2001) 305-339.
[39] C.J. Walters, C.S. Holling, Large-Scale Management Experiments and Learning by Doing, Ecology 71(6) (1990) 2060-2068.
[40] S.T. Buckland, D.R. Anderson, K.P. Burnham, J.L. Laake, D.L. Borchers, L. Thomas, Introduction to distance sampling: estimating abundance of biological populations, Oxford University Press2001.
[41] E. Cordes, D. Jones, T. Schlacher, D. Amon, A. Bernardino, S. Brooke, R. Carney, D. DeLeo, K. Dunlop, E. Escobar-Briones, A. Gates, L. Génio, J. Gobin, L.-A. Henry, S. Herrera, S. Hoyt, S. Joye, S. Kark, N. Mestre, A. Metaxas, S. Pfeifer, K. Sink, A. Sweetman, U. Witte, Environmental impacts of the deep-water oil and gas industry: a review to guide management strategies, Frontiers in Environmental Science 4(58) (2016).
[42] A.J. Underwood, Beyond BACI - Experimental-Designs for Detecting Human Environmental Impacts on Temporal Variations in Natural- Populations, Australian Journal of Marine and Freshwater Research 42(5) (1991) 569-587.
[43] J.M. Durden, L.E. Lallier, K. Murphy, A. Jaeckel, K. Gjerde, D.O.B. Jones, Environmental Impact Assessment process for deep-sea mining in 'the Area', Marine Policy 87 (2018) 194–202.
[44] J.M. Durden, K. Murphy, A. Jaeckel, C.L. Van Dover, S. Christiansen, K. Gjerde, A. Ortega, D.O.B. Jones, A procedural framework for robust environmental management of deep-sea mining projects using a conceptual model, Marine Policy 84 (2017) 193-201.
[45] J.M. Durden, B.J. Bett, D.O.B. Jones, V.A.I. Huvenne, H.A. Ruhl, Abyssal hills – hidden source of increased habitat heterogeneity, benthic megafaunal biomass and diversity in the deep sea, Prog. Oceanogr. 137, Part A (2015) 209-218.
[46] W.G. Cochran, Sampling techniques., John Wiley Sampling techniques, Oxford, England, 1953.
[47] J.A. Jankowski, A. Malcherek, W. Zielke, Numerical modeling of suspended sediment due to deep-sea mining, Journal of Geophysical Research: Oceans 101(C2) (1996) 3545-3560.
[48] C. Ruhlemann, S. Knodt, Manganese Nodule Exploration & Exploitation from the Deep Sea, Journal of Ocean Technology 10(1) (2015) 13-21.
[49] H.C. Trannum, H.C. Nilsson, M.T. Schaanning, S. Øxnevad, Effects of sedimentation from water-based drill cuttings and natural sediment on benthic macrofaunal community structure and ecosystem processes, J. Exp. Mar. Biol. Ecol. 383(2) (2010) 111-121.
[50] M.T. Schaanning, H.C. Trannum, S. Øxnevad, J. Carroll, T. Bakke, Effects of drill cuttings on biogeochemical fluxes and macrobenthos of marine sediments, J. Exp. Mar. Biol. Ecol. 361(1) (2008) 49-57.
[51] R. Sharma, B.N. Nath, G. Parthiban, S.J. Sankar, Sediment redistribution during simulated benthic disturbance and its implications on deep seabed mining, Deep-Sea Res. Pt. II 48(16) (2001) 3363-3380.
[52] R. Kotlinski, V. Stoyanova, Physical, Chemical, and Geological changes of Marine Environment Caused by the Benthic Impact Experiment at the IOM BIE Site, Proceedings of the 8th International Offshore and Polar Engineering Conference, May 24-29, 1998, Montreal, Canada, 1998, pp. 277-281.
[53] E. Ozturgut, D.D. Trueblood, J. Lawless, An overview of the United States' Benthic Impact Experiment, Proceedings of International Symposium on Environmental Studies for Deep-Sea Mining, Metal Mining Agency of Japan, Tokyo, 1997, pp. 23-31.
[54] T. Fukushima, Overview "Japan Deep-Sea Impact Experiment = JET" Proceedings of ISOPE Ocean Mining Symposium, November 21-22, 1995, Tsukuba, Japan. , 1995, pp. 47-53.
[55] E. Desa, INDEX project group, Initial results of India's environmental impact assessment of nodule mining, Proceedings of International Symposium on Environmental Studies for Deep-Sea Mining, November 20-21, 1997, Tokyo, Japan. , 1997, pp. 49-63.
[56] H. Rye, M. Reed, N. Ekrol, The PARTRACK model for calculation of the spreading and deposition of drilling mud, chemicals and drill cuttings, Environmental Modelling & Software 13(5-6) (1998) 431-441.

[57] J.D. Wirth, The Trail Smelter Dispute: Canadians and Americans Confront Transboundary Pollution, 1927–41, Environmental History 1(2) (1996) 34-51.

[58] J.A. Ardron, R. Rayfuse, K. Gjerde, R. Warner, The sustainable use and conservation of biodiversity in ABNJ: What can be achieved using existing international agreements?, Marine Policy 49 (2014) 98-108.

[59] H.A. Ruhl, M. André, L. Beranzoli, M. Namik Çagatay, A. Colaço, M. Cannat, J.J. Dañobeitia, P. Favali, L. Géli, M. Gillooly, J. Greinert, P.O.J. Hall, R. Huber, J. Karstensen, R.S. Lampitt, K.E. Larkin, V. Lykousis, J. Mienert, J. Miguel Miranda, R. Person, I.G. Priede, I. Puillat, L. Thomsen, C. Waldmann, Societal need for improved understanding of climate change, anthropogenic impacts, and geo-hazard warning drive development of ocean observatories in European Seas, Prog. Oceanogr. 91(1) (2011) 1-33.

[60] J.A. Ardron, Transparency in the operations of the International Seabed Authority: An initial assessment, Marine Policy (2016).

[61] J.A. Ardron, H.A. Ruhl, D.O.B. Jones, Incorporating transparency into the governance of deep-seabed mining in the Area beyond national jurisdiction, Marine Policy 89 (2018) 58-66.