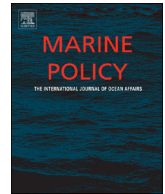




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Environmental considerations for impact and preservation reference zones for deep-sea polymetallic nodule mining

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ABSTRACT

Development of guidance for environmental management of the deep-sea mining industry is important as contractors plan to move from exploration to exploitation activities. Two priorities for environmental management are monitoring and mitigating the impacts and effects of activities. International regulation of deep-sea mining activities stipulates the creation of two types of zones for local monitoring within a claim, impact reference zones (IRZ) and preservation reference zones (PRZ). The approach used for allocating and assessing these zones will affect what impacts can be measured, and hence taken into account and managed. This paper recommends key considerations for establishing these reference zones for polymetallic nodule mining. We recommend that zones should be suitably large (Recommendation 1) and have sufficient separation (R2) to allow for repeat monitoring of representative impacted and control sites. Zones should be objectively defined following best-practice and statistically robust approaches (R3). This will include the designation of multiple PRZ and IRZ (R4) for each claim. PRZs should be representative of the mined area, and thus should contain high -quality resource (R5) but PRZs in other habitats could also be valuable (R6). Sediment plumes will influence design of PRZ and may need additional IRZ to monitor their effects (R7), which may extend beyond the boundaries of a claim (R8). The impacts of other expected changes should be taken into account (R9). Sharing PRZ design, placement, and monitoring could be considered amongst adjacent claims (R10). Monitoring should be independently verified to enhance public trust and stakeholder support (R11).

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

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Table 1
 Examples of how the three different DSM resource types will require different monitoring regimes. This table includes a simplified and general overview of the ecological considerations of particular importance to monitoring.

Mineral type	Expected direct footprint	Secondary impact plume dispersal considerations.	Ecological considerations particular to monitoring the mining resource	Expected time scale for recovery	Implications for monitoring
Nodules	Large (100 s – 1000 s km ²)	Generally low but variable currents at the deep seafloor suggest that plumes will be dispersed in all directions. Seafloor dominated by fine sediments – typically more so than either SMS or crusts.	Broad-scale regional stratification cause by a range of physical and biological factors, such as carbon flux from surface waters. Local communities influenced by habitat heterogeneity, including geomorphology and nodules as habitat. High biodiversity of most groups, but generally lower abundances than either SMS or crusts.	Very slow	Low abundances and high biodiversity suggest low statistical power to detect change in all but the most common species. Improving power requires large sample sizes and many replicates. Monitoring may need to be augmented with modelling to infer higher level changes (e.g. to species richness / biodiversity, respiration, re-mineralisation, etc.). Overall very slow recovery suggests very long term monitoring will be required.
SMS	Small (10 s km ²)	Geomorphology of some vent areas can lead to prevailing current regimes (e.g. along ridges). Plumes from operations near active vents could become entrained in the vertical transport of heated water, prolonging their suspension throughout the water column, with increased dispersal distances.	Very highly stratified local communities, according to distance from active vent sites (i.e. local energy regimes). Active sites have high abundances, but lower biodiversity, whereas inactive neighbouring sites have much lower abundances but potentially higher biodiversity. Likely larger temporal variability than either nodules or crusts.	Highly variable	High stratification of ecology will need to be reflected in monitoring, with sample sizes, replicates, and time series matched to the each of the ecological communities. May be difficult to find representative control sites. High temporal variability of some sites suggests the need for additional replicates to insure against some of these changing their nature (e.g. from active to inactive venting, or vice versa), disqualifying them from detecting changes caused by mining. Possible pelagic (re-) suspension of plumes by nearby active sites will need to be factored in on a site-by-site basis.
Crusts	Medium (10–100 s km ²)	In mining seamounts, much of the plume may be dispersed directly into the water column, higher above the surrounding seabed than for other mineral types. Sediments will be comprised of fewer fines than for either nodules or SMS. The heavier particles can be expected to accumulate and may lead to submarine sediment movements.	Vertically stratified communities at a local scale, and by seamount groupings at a regional scale (with each seamount in a grouping still being unique in certain ways). Seamount biodiversity is often higher than surrounding areas, with the potential for increased endemicity in some cases. Many pelagic animals are associated with seamounts including protected marine mammals and commercially important fish species.	Slow and somewhat variable	Vertical stratification of communities suggests a need to vertically stratify monitoring as well –both benthic and pelagic. The quasi-uniqueness of each seamount suggests placement of PRZs on the same seamount, whenever possible. If not possible to find unaffected representative areas (for each stratum) on the seamount, statistical power will need to be regained through increased number of replicates on a neighbouring one(s). Monitoring impacts on a neighbouring species will need to be designed on a case-by-case basis, dependent on their biology. Monitoring possible long range pelagic effects will require widely dispersed sampling. Negative effects detected on fish species of commercial interest or on protected ‘red-listed’ species may necessitate management trade-offs, as well as additional legal responsibilities (outside the scope of this paper).

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 dewatering 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 fine-grained 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. 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.

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:

Table 2

Specific management questions for deep-sea mining addressed by designation of appropriate PRZs and IRZs. Setting up a robust network of PRZs and IRZs can avoid costs through additional environmental work, delays or even cessation of activities associated with regulatory non-compliance.

Issue	Why important	How addressed
Characterising the impact of mining activities	The central question to be addressed, which will be legally required in the mining contract and associated monitoring plan.	Quantification of mining impact (specific impacts, magnitude, extent) by comparing PRZs and IRZs
Separating mining impacts from natural environmental change	Otherwise, mining activities may be held responsible for impacts that were caused by other factors.	Quantification of natural environmental change in long-term time-series at PRZs. PRZs must be large enough to have viable faunal populations over the term of the monitoring
Evaluation of the efficacy of management/mitigation measures	Build knowledge base and inform future management. Necessary for adaptive management.	Compare monitoring data from different mining projects PRZs and IRZs to evaluate the efficacy of their respective mitigation measures. Experiments could be established within and across mining blocks to more rigorously assess mitigation measures as part of active adaptive management.
Assessment of recovery from mining activities	Inform the timing of the release of future mining blocks. Reveal long-term trends in impacted and un-impacted communities	Long term time-series comparisons between PRZs and IRZs. Both zones need to be in place for long timeframes and not impacted by future activities.
Reduce uncertainty and necessary precautionary margin	Reducing uncertainty in ecosystem responses to mining will allow more effective and directed monitoring indicators to be selected, more meaningful environmental quality targets, and will clarify the amount of precaution needed (e.g. buffer zones to account for variability in plume dispersal). It may also require fewer measurements to be taken in subsequent monitoring programmes.	Evaluation of specific impacts across sites by comparing long-term data at PRZs and IRZs.
Ensure compliance with relevant regulations and best practices	It is vital to have robust data to demonstrate compliance; i.e. the environmental objectives of the approved work plan.	Compare impacts (as assessed from comparison of PRZs with IRZs) to protected species, habitats, policy targets or performance indicators.
Improve regional environmental management	Help integrate project-scale environmental management with regional and strategic approaches. A network of PRZs, if maintained as long-term monitoring sites, will enhance the role of larger areas designated for environmental protection, such as APEIs.	Results from project-specific monitoring of PRZs and IRZs would feed into strategic / regional assessments of cumulative and transboundary impacts
Ensure examples of representative habitat are locally preserved	Conserving habitat locally representative of mining areas is necessary to enhance the probability of recovery of impacted sites through local re-colonisation.	PRZs, if maintained as long-term monitoring sites, may act as partial conservation sites if large enough to sustain viable populations of some species (but outside the scope of this paper)

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 minimise 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 license.

Fig. 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’

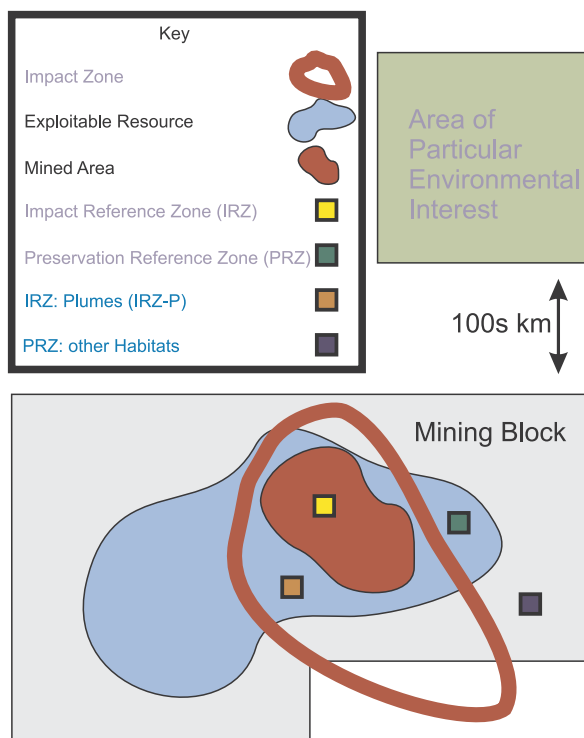


Fig. 1. A graphical representation of PRZ and IRZ as set out in the ISA mining code and in recommendations presented here. Text in purple refers to areas already defined under the Mining Code. Blue text refers to additional areas recommended here. We recommend multiple zones, but only single IRZ/PRZ are shown to improve clarity. The relative size of each area depicted was only chosen for clarity and is not intended as a recommendation.

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.

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 Fig. 2.

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

Box 1

: Conservation Considerations.

PRZ, being “areas in which no mining shall occur”, are de facto marine conservation areas. Protected areas have been shown in other environments to be an effective mechanism for preserving biodiversity [62] and can increase density, biomass, size and diversity of shallow water marine organisms compared with areas outside the reserve [63]. The ability of protected areas to perform these roles hinges upon several factors, foremost of which is size (i.e. whether they are large enough to support viable populations of organisms affected by mining), and secondly their spacing, such that they can remain ecologically connected to each other and the impacted mining areas. Other important characteristics identified in shallower water environments are: (1) that reserves do not permit any exploitation activities, (2) they are ecologically contained (isolated) and (3) that they are well enforced and have a long duration of protection [64]. In the context of DSM and the current management regime, some conditions could be relatively easily met. However, determination of size and spacing will likely require further consideration. The interaction of claim-scale protected areas and the regional-scale APEIs will also likely be important for an effective conservation strategy.

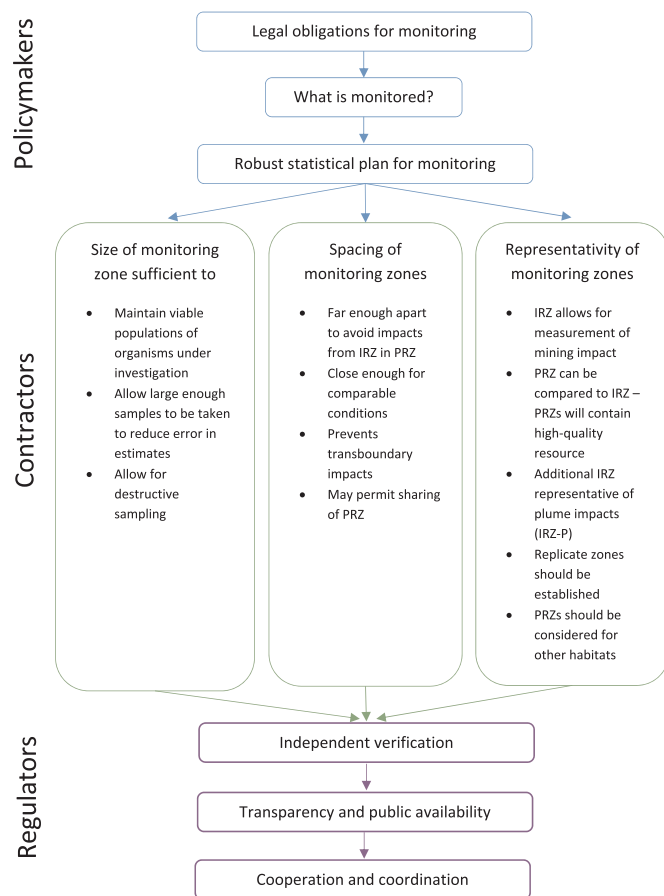


Fig. 2. Summary of the considerations for monitoring of deep-sea mining impacts presented in this paper. We focus on claim-scale monitoring in impact reference zones (IRZ) and preservation reference zones (PRZ).

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-sea-floor 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 (Fig. 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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