An operational risk-based process to assess and avoid serious harm in the deep sea

Project: Integrated Ecosystem Assessment and Ecosystem-Based Management Framework for Polymetallic Nodule Collection Activities

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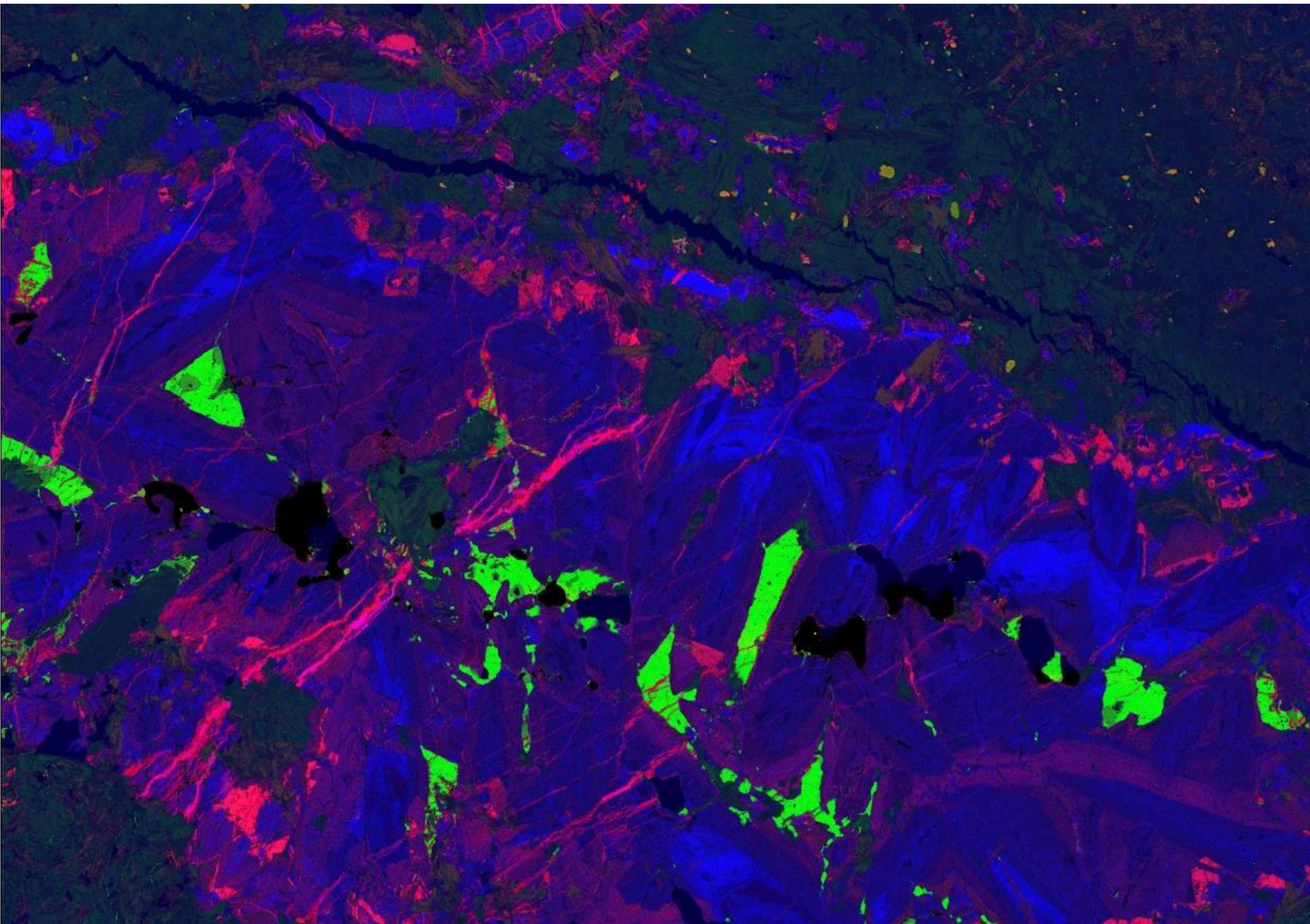

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Executive summary

This report presents a structured, precautionary framework for managing the environmental risks associated with deep-sea mining (DSM), a nascent industry with high ecological uncertainty. The concept of serious harm is rooted in international law, particularly the United Nations Convention on the Law of the Sea (UNCLOS) and the concept is being operationalized by the International Seabed Authority (ISA). However, there is no generally accepted definition or method for assessing serious harm. The report proposes a risk-based, hierarchical process that integrates both input controls (managing pressures like sediment plumes, noise, and light) and outcome controls (monitoring ecosystem responses such as species abundance and functional integrity).

Central to the framework is the concept of a receptor, which refers to any ecosystem component—species, habitat, or function—that may be affected by mining. The process begins with a pessimistic precautionary assumption of complete loss of receptors in impacted areas, which can be refined through ongoing monitoring and adaptive management. This assumption can be subsequently relaxed if monitoring of mine impacted areas can demonstrate there has been less than a complete loss of a receptor or if, over time, the has been recovery.

The proposed six-step hierarchical process involves:

1. Risk Reduction: Identifying potential interactions between mining pressures and ecosystem receptors.
2. Qualitative Modelling: Understanding cumulative impacts and ecosystem pathways.
3. Relative Risk Ranking: Using expert-based multi-attribute analysis to prioritize high-risk interactions.
4. Quantitative Risk Assessment: Applying data-driven models to estimate loss and recovery.
5. Setting Limits: Defining thresholds for serious harm based on pessimistic assumptions.
6. Adaptive Management: Monitoring ecosystem responses and adjusting operations to stay within defined limits.

Two critical decisions for regulators are emphasized: determining the spatial extent of the receptor (N) and setting limits to avoid serious harm.

The framework incentivises monitoring and data collection, allowing proponents to demonstrate that observed loss is less than initially assumed and that recovery may be occurring. This adaptive approach enables mining to proceed cautiously while ensuring that operations remain within ecological boundaries.

In conclusion, the report offers a novel, science-based methodology that could be adopted for regulating DSM in the presence of relatively high levels of uncertainty of impacts to deep sea ecosystems It provides regulators with tools to define and avoid serious harm, while giving industry a pathway to demonstrate environmental responsibility through monitoring and adaptive management.

1 Introduction

1.1 Would you drive with your eyes shut?

Arriving in a new country and hiring a car from the airport can be a challenging experience. Navigating new roads, potentially new rules and avoiding hazards to arrive at your destination is fraught with uncertainty. Now suppose instructions from the car-hire company were to keep your eyes closed, never push the accelerator more than 30% and always turn left – would you reach your destination? A safe and successful journey requires, at an operational level, the setting of a desired destination or objective and the coordination of inputs to the car (*i.e.*, accelerator, steering, brake, steering) with outcomes (*i.e.*, staying in your lane, on the road and out of the ditch). By way of analogy, deep-sea mining is entering uncharted territory as a nascent industry yet to commence commercial-scale operations. There is great uncertainty about the road ahead, with much discussion about the right way to commence, steer, and brake. Much of this uncertainty is based on negative effects that deep-sea mining might have on deep-sea ecosystems, and a lack of clarity about how to manage inputs to achieve desired outcomes.

High levels of uncertainty and concern are held by proponent, regulator, and public alike, and for commercial operations to commence there needs to be an assurance, on the one hand, that ecological values are protected and serious harm is avoided, and on the other, that the management of mining operations is clear, transparent and practical to implement, both from the perspective and needs of the regulator and of the proponent. This lack of assurance has led to an impasse, with divergent views on how best to proceed, or if at all. We propose an approach based on experiences drawn from exploited ecosystems to resolve some of the key sticking points in the environmental management of deep-sea mining, and to provide options and decision points for its management. We use an operational definition of serious harm as the key nexus of the approach.

1.2 Quantifying Serious Harm

The term "serious harm" is introduced in Article 165 of UNCLOS and the International Seabed Authority (ISA) has responsibility for making recommendations to avoid serious harm. The ISA council is currently drafting regulations where serious harm "means any effect from activities in the Area on the Marine Environment which represents a significant adverse change in the Marine Environment determined according to the rules, regulations and procedures adopted by the Authority on the basis of internationally recognized standards and practices informed by Best Available Scientific Evidence" (ISA 2019). But there is significant uncertainty about what serious harm might be and even more uncertainty about how it can be avoided. There is no currently agreed definition of serious harm, and significant uncertainty exists around what this might entail (Leduc *et al*. 2024). Leduc *et al*. (2024) considered how serious harm could be defined and operationalized, noting the experiences from other sectors, and proposed an approach where management actions should be taken, including a threshold where there is increased scrutiny of the effects of deep-sea mining, and a limit where mining operations must be stopped.

1.3 Input- and outcome-based management

One of the most important lessons in learning to drive a car is to coordinate inputs and outcomes; if only inputs are used you inevitably end up over the centre line, off the road or worse; and if only outcomes are used you end up going nowhere. Within the ISA DSM framework, controls on inputs would be equivalent to controls on the impacts (or pressures) of activities (*i.e*., extent and concentration of plumes, extent and intensity of noise and light) and controls on outcomes would be equivalent to controls on the cumulative effects of activities (*i.e.*, decline in species abundance, ecosystem functions and services). Here, we employ the definitions for impact and effect as per ISA (2022), where impact is the influence of an action or activity during the project on the environment and effect is the consequence or outcome of an action or activity during the project on the environment (cf. Leduc *et al*. (2024)). Leduc *et al*. (2024) identified that adaptive management will require controls on both inputs and outcomes.

There have been extensive applications of input- and outcome-based management in other sectors, especially fisheries—through harvest management strategies, where levels of fishing effort or landed catch are managed based on outcomes for stock status and the long term sustainability of the fishery (Smith *et al*. (2013), Dichmont *et al*. (2012), Yamazaki *et al*. (2009)). Here, experience suggests that to satisfy the dual objectives of healthy stock status and viable fisheries (economically and socially) then a combination of input and outcome controls provide the best overall result.

Key to effectively implementing this approach in fisheries has been the use of precautionary risk assessments coupled with robust models that can be updated with new data for high risk activities. For this we look to the thinking that underpins the Ecological Risk Assessment for the Effects of Fishing (ERAEF) and its use in the adaptive management (Hobday *et al*. (2011), Zhou *et al*. (2016)). The ERAEF hierarchical approach uses progressively more complex and data intensive methods to eliminate low risk activities and focus effort on high risk activities. The approach is underlined by the Scale, Intensity, Consequence Analysis (SICA), Productivity, Susceptibility Analysis (PSA), and Sustainability Assessment for Fishing Effects (SAFE) approaches. SICA and PSA are used progressively to implement robust screening processes that identify high risk activities, which are then analysed quantitatively in more detail in the SAFE process. SICA is an expert-based screening process, PSA is a qualitative process that uses expert assessment of life history and exposure to derive a relative score, and SAFE and other more complex assessments, range from the inclusion of explicit fishery footprints and population biology up to full species-specific stock assessments. Some thinking on the application of ERAEF approaches has been expanded to broader cumulative ecosystem effects in Fulton *et al*.(2023). Here, we use concepts that underlie the ERAEF and broader cumulative effects assessment to develop a hierarchical risk-based process to inform decision making in deep-sea mining.

Developing a full risk, consequence and recovery framework for deep-sea mining activities represents a challenge in a low data area. There is currently limited data and information about deep-sea species and ecosystems, or impacts of DSM, and estimating risk from mining operations is difficult, as is predicting likely future ecosystem states. If there are only input controls (*i.e.*, management is only responding to the levels of input), then the most precautionary approach is to pessimistically assume total ecosystem function and biodiversity loss under the footprint of an activity. Furthermore, in the absence of monitoring it is assumed that this loss is permanent and there is no recovery of species, functions or services, which would lead to an abrupt cessation of mining as the footprint approached agreed limits. For mining activities to proceed any further would require monitoring of ecosystems and their functions and services (*i.e*., a means of quantifying level of effect which informs outcome controls). This monitoring would need to demonstrate to regulators that the ecosystem is staying within agreed limits that define and prevent serious harm.

We define a receptor as any structural component of an ecosystem that may be affected by an activity, such as a population, species, community, habitat or ecosystem, or functional component, such as trophic groups, bentho-pelagic coupling or benthic mineralisation rates (Leduc *et al*. (2024)). Any pressure can potentially cause loss of the abundance or quality of the receptor, the magnitude of which may range from small to large relative to the population (or functional process magnitude). The receptor is also capable of recovery over time, but the magnitude of that recovery may be non-existent, small or large.

The intent of the risk, consequence and recovery framework is to attempt to ensure that operations never cause effects that cross thresholds and limits by managing input levels to ensure that outcomes (*i.e.*, level of receptor) never exceed the limit set on the receptor. Implementation will require clear identification of thresholds and limits for each receptor (cf. Leduc *et al.* 2024), as well as robust monitoring process and methods of assessment that identify impact pathways and points of intervention.

2 A hierarchical process for Risk, Consequence and Recovery in deep-sea mining activities

Prior to any deep-sea mining related activity commencing there needs to be an evaluation of effects on the environment founded on clear and transparent assessment criteria and a robust evidence base (International Seabed Authority 2022). We present an approach based on previous experience on how such a process might occur. It is a process of de-risking that relies on an ability to test assumptions with data and is support of a long-term monitoring program. This approach builds and adapts previous work on integrated assessments and cumulative effects from Hobday *et al*. (2011), Hayes *et al*. (2015), Dunstan *et al*. (2019) and Fulton, Dunstan, and Treblico (2023).

1. In ISBA/27/C/4 there are four terms considered in the calculation of effects: susceptibility, intensity, extent, and duration. There is a need to carefully define these terms so they can be communicated clearly, and they can be estimated with existing or future data.
2. We assume that each receptor is distributed randomly (but not evenly) across the domain of interest—the grid. This domain does not need to be a grid but could be any area or volume that encompasses the receptors distribution. This grid of cells represents the functional habitat extent for the species, group, or ecosystem function. We assume that spatial variation in population density and equivalent for ecosystem function does not have to be considered as a term in this calculation. Note that the same assumptions are made in Zhou *et al*. (2016). Failure of this assumption will necessitate increased spatial data to identify the spatial patterns of the receptor.
3. Recovery post mining operations in the cell (*i)* will be a function of the growth rate, which in this initial application has been decomposed into a Michaelis–Menten curve. This assumption can be relaxed, or other forms of recovery functions applied.
4. A mining operation occurs sequentially through space and time. It is assumed that any defined cell in the grid (*i*) will be mined once and not mined again. Broadly distributed pressures (*i.e*., mid-water return plume, noise, light) however, can cause ongoing or intermittent impacts to a cell in the grid until mining operations cease.

To implement outcome controls, we need to have some way of measuring the change in the receptor relative to the total population or abundance of the receptor and have a clear means of linking that back to the pressure (*e.g*. through direct mortality caused by removal). We assume that the receptor is arranged on a grid of dimensions (*e.g.*, 10x10, with 100 potential cells that could be mined) that overlaps with the mine-impacted area. Note that a grid is used as an example and the extent of the receptor can be any shape or volume.

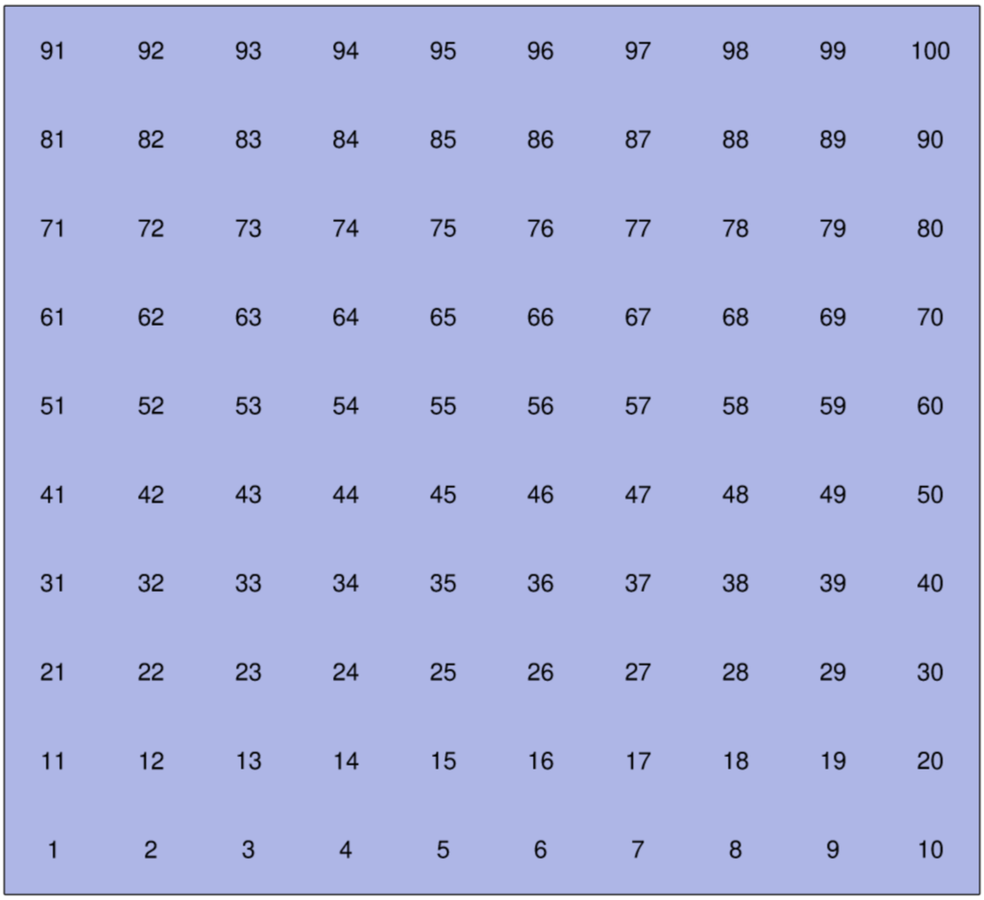

Figure 1 Illustrative example of a grid containing a receptor that will be mined

For each cell (*i*) on the grid that has been impacted by mining the current abundance or quantity will be:

$$R_{\{i,,t\}} = \frac{N_{\{i\}} - L_{\{i\}} + Rec_{\{i,t\}}}{N_{\{i\}}} \quad (1)$$

Where:

$R_{\{i,t\}}$ = The receptor current quality or abundance of the receptor in cell *i* at time *t* after mining has occurred.

$N_{\{i\}}$ = The baseline receptor quantity or abundance prior to mining
$L_{\{i\}}$ = The change in receptor quality or abundance post mining
$Rec_{\{i,t\}}$ = Recovery in cell *i* at time *t* after mining impacts have ceased.

Over the entire mine-impacted area (m cells on the grid of 100 cells) of the receptor the current quality or abundance

$$R_{\{t\}} = \frac{\Sigma_{\{i=1\}}^{\{i=100\}}(N_{\{i\}}) - \Sigma_{\{j=1\}}^{\{j=m\}}(L_{\{j\}}) + \Sigma_{\{j=1\}}^{\{j=m\}}(Rec_{\{j,t\}})}{\Sigma_{\{i=1\}}^{\{i=100\}} N_{\{i\}}} \quad (2)$$

And removing the sums to simplify

$$R_{\{t\}} = 1 - \frac{L}{N} + \frac{Rec_{\{t\}}}{N} \quad (3)$$

Input control relies on only managing the input components to L that are the direct pressures (*e.g.*, level of mining activity in an area). Successfully using only input controls relies on accurately estimating the link between the input limits and the resulting influence on the receptors correct across all possible ecosystem receptors, ideally accounting for all possible ecosystem interactions. Full ecosystem management is not a trivial task, as shown by ecosystem- based fisheries management (Plagányi *et al.* 2014) – akin to driving with your eyes closed without a map. In particular, the concept of allowing for adaptively managing direct and indirect cumulative ecosystem impacts is an approach that has a very short history and has not yet been successfully linked to management decision-making in any environmental management field to the authors' knowledge. Outcome controls rely on managing the realized level of effect on the values of $Receptor$, accounting for the cumulative nature of impacts, so that the state of the $Receptor$ does not reach exceed the limit for serious harm (c.f. Leduc *et al*. (2024)). The equivalent in fisheries is managing catch rather than effort. In deep-sea mining the distinction between input and outcome control is less clear cut, but it would equate to managing the level of mortality caused by mining operations, which would equate to managing the pressures into the system (*i.e*., input controls) to prevent the reduction in the value of $Receptor$ below an identified limit. In essence, the degree of effect caused is tracked so the level of activity can be adaptively adjusted.

2.1 A hierarchical process

Building on previous work, we outline a hierarchical process that can be used to mitigate risks of causing serious harm and key assumptions that permit a precautionary approach to beginning operations while incentivizing monitoring to identify if effects of operations are nearing limits.

Step 1. Simple risk reduction: using a matrix of potential interactions between ecosystem receptors (*e.g*., an objective-indicator matrix or value impact-matrix, Hayes *et al.* 2015), where potential links between pressures from mining activities and impact receptors are identified. This will reduce the total number of potential interactions.

Step 2 Qualitative ecosystems models: to identify the links between pressures and ecosystem receptors, and how impacts can propagate through ecosystems to generate cumulative impacts of multiple pressures on those ecosystems and identify candidate indicators (Hayes *et al*. 2015, Hyman *et al*. 2025).

Step 3 Relative Risk: Qualitative effect calculation to establish the relative importance of different pressures and impacts on ecosystem components and to explicitly identify where different avoidance or mitigation measures might be applied.

Step 4 Quantitative Risk Assessment: Quantitative ecosystem risk analysis for pressure-receptor interactions that are identified as relative high-risk pressure receptor scenarios (*e.g*., Zhou *et al*. (2016), see Woolley *et al.* (2025) for deep-sea mining analysis).

To this point, the process is similar to that of the ERAEF outlined in Hobday *et al*. (2011) and proposed for cumulative effects in Dunstan *et al*. (2019) and Fulton et al. (2023) with removal of low-risk pressures and increasingly more robust quantitative assessments for higher risk activities.

These processes rely on getting the qualitative assessments correct first to rank risks relative to each other and then performing quantitative assessments for the high ranked risks.

To implement harvest management strategies (cf. Smith *et al*. (2013)), fisheries assessments rely on an understanding of a pre-fishery reference state to guide the selection of limits and a robust monitoring program to ensure that the desired state of fisheries is being attained (*i.e*., through input and outcome controls). To implement this approach for deep-sea mining, we suggest additional steps below to ensure that ecosystems are managed to avoid crossing any $Limit$ (Leduc *et al*. (2024)).

Step 5 Set a Limit: Using a *provisionally pessimistic* (*i.e*., complete loss of a given ecosystem component) assumption about the impacts of mining, assess the likely footprint of pressures on high risk (*i.e*., step 4) ecosystem components and assign a limit to define serious harm. This assumption is a precautionary approach to managing the extreme uncertainty of potential impacts and effects of deep-sea mining.

Step 6. Adaptive management: Establish a robust monitoring programme to assess the response of $Receptor$ with respect to the reference state or pre-mining area identified N and then adjust activity levels so the $Receptor$ never exceeds the $Limit$ set by the ISA. This approach will reduce the uncertainty in the scale of loss and potential recovery.

We note that step 1 is done as a matter of course through all assessments, and step 2 has been explored in detail in Hyman *et al*. (2025). Details of an ecosystem approach to quantitative risk assessment (step 4) is shown in Woolley *et al*. (2025). We work through step 3, 5 and 6 below.

2.2 Step 3: Relative Risk

Once there is a clear understanding of the potential pressures (step 1) and impact pathways and potential significant effects (step 2), it is desirable to rank the risks from least to most serious. An approach to do this is through an expert process that assigns a score to different attributes of impact and effect . Multi-attribute value analysis (Keeney and Raiffa 1993) is a structured framework that combines expert scoring of impact factors within each attribute, and the relative importance of each attribute to assess overall impact on valued quantities. The construction of an approach to relative risk depends on the definition of impact factors and attributes for a defined biological metric of value. For example, a mining activity may produce two different attributes of impact, such as substratum compaction and contamination, on a defined biological metric, such as the biomass of a functional group. In the analysis, experts score the activity for each attribute. The effects of the two attributes are then weighted differently by the experts, and this weighting would likely depend on the choice of biological metric (*e.g*., benthic infauna versus mobile macrofauna). The multi-attribute value analysis can also be extended to evaluate utility functions (Keeney and Raiffa 1993) by incorporating probabilistic assessments from experts.

High risk activities can then be prioritized for more quantitative assessment based on the relative effects on receptors. If the ranking is correct then high risk receptors should respond faster to impact, and any limits will be reached first. The logic is that any impact will occur over a proportion of the area that the receptor is distributed over. We then need to estimate the relative change in the receptor. We can calculate the instantaneous loss of a mined cell in the grid cell (j) as at any point in time as:

$$L_{\{j\}} = S(g, p, d, j, \ldots)I(p, d, j, \ldots)E(p, d, j, \ldots) \quad (4)$$

$S(g, I, j, \ldots)$ = the function for susceptibility response of an individual unit of a Receptor (*g*) to the pressure *p*, per unit pressure, assuming a fixed time period of operations *d*, with potential additional covariates (*e.g.*, depth, functional response to different pressures).

$I(p, j, \ldots)$ = the function for the intensity of pressure *p* over a fixed time period *d*, with additional covariates within the cell (*j*).

$D(p, j)$ = the duration that the pressure is acting within the cell (*j*).

$E(p, j, \ldots)$ = the function for the spatial extent of zone of impact (m^2 or m^3) within the grid cell (*j*), as defined by additional covariates.

Each of these functions respectively gives the susceptibility of the receptor to the pressure, the intensity of the pressure, and the duration and extent that the pressure occurs over operations within the cell. For the total area mined across the entire extent of the grid (100 cells) for *m* mined cells, recalling (2) gives:

$$R_{\{t\}} = \frac{\Sigma_{\{i=1\}}^{\{i=100\}}(N_{\{i\}}) - \Sigma_{\{j=1\}}^{\{j=m\}}\left(S(g,p,i,j,\ldots)I(p,i,j,\ldots)E(p,i,j,\ldots)\,D(p,i,j)\right)}{\Sigma_{\{i=1\}}^{\{i=100\}}N_{\{i\}}} \quad (5)$$

Following this logic, the total duration of activities will be $\Sigma_{\{j=1\}}^{\{j=m\}}\ D(p, j)$.

Or

$$R_{\{t\}} = \frac{total\ abundance\ of\ the\ receptor - loss\ due\ to\ mining}{total\ abundance\ of\ the\ receptor}$$

Values for the terms of *S*, *I*, *D*, *E* can be qualitatively ranked low to high, which will give a relative ranking of risks to ecosystems. The ranking can identify key points where avoidance and mitigation may play a role and provide a series of discrete points where impacts can be reduced. In addition, this ranking can map to the mitigation hierarchy (processes to avoid, minimise, restore, offset impacts) used in environmental management practice:

1. Reduce the susceptibility of the receptor to the pressure, most easily through avoiding any interaction with the value—equivalent to “avoid”. The value may also be naturally resistant to the pressure.
2. Reduction of the intensity of the pressure, primarily through technical means—equivalent to “minimise”.
3. Reduction in the extent or duration of the pressure relative to the total population through technical or physical processes, so that only a small portion of the total population would be impacted—equivalent to “minimise”.

These three points of intervention are input controls (*i.e.*, they modify the pressures coming into the ecosystem) and modify the values of *I*, *D*, *E*. Note at this point we do not consider the option to restore or offset.

2.3 Step 4: Quantitative Risk Assessment

Quantitative risk assessment is explored in Woolley *et al*. (2025) and will not be discussed further here. This form of quantitative assessment allows for the estimation of the values of SIDE. It allows for the variation in species in space and time and gives a quantitative estimate of loss from initial activity of a specific area and any potential recovery that can be seen from data. This approach allows for the quantitative estimation of risk (*i.e.*, both consequence and likelihood) and updated estimations of consequence and any recovery through time with new monitoring data.

2.4 Step 5: Calculation of Limits of Serious Harm

The initial starting assumption is that there will be a complete loss of a given value within a grid cell that is impacted by mining operations (Fig. 2—Complete loss). This assumes that whenever a grid cell is mined or otherwise impacted by mining operations, then all ecosystem components and values (*i.e.*, the $Receptor$) of interest are lost and there is no recovery. This assumption can be tested through post-mining monitoring and analysis where different levels of initial loss are likely and impacts of DSM assessed.

We are assuming that in every cell where mining occurs $L_{\{j\}} = N_{\{j\}}$. We use limit as defined using the approach of Leduc *et al*. (2024) which is the value of $Receptor$ when significant and serious harm, respectively, is reached, and operations must be modified or stopped, respectively. If we assume that ecosystem components are distributed randomly across the entire mining area, then the limit becomes the proportion of the mined area to the total area.

Operations can continue while

$$Limit < 1 - \frac{\Sigma_{\{j=1\}}^{\{j=m\}} E(p, j, \ldots))}{\Sigma_{\{i=1\}}^{\{i=100\}} N_{\{i\}}} \tag{6}$$

or

$$Limit < 1 - \frac{Total\ extent\ of\ mined\ area}{\text{Total area of the receptor}}$$

We explore several potential scenarios where a provisionally pessimistic assumption about complete loss of an ecosystem component is made with different forms of potential recovery, including no recovery (Fig. 2). Each scenario assumes an initial loss of all of the $Receptor$ when mining occurs.

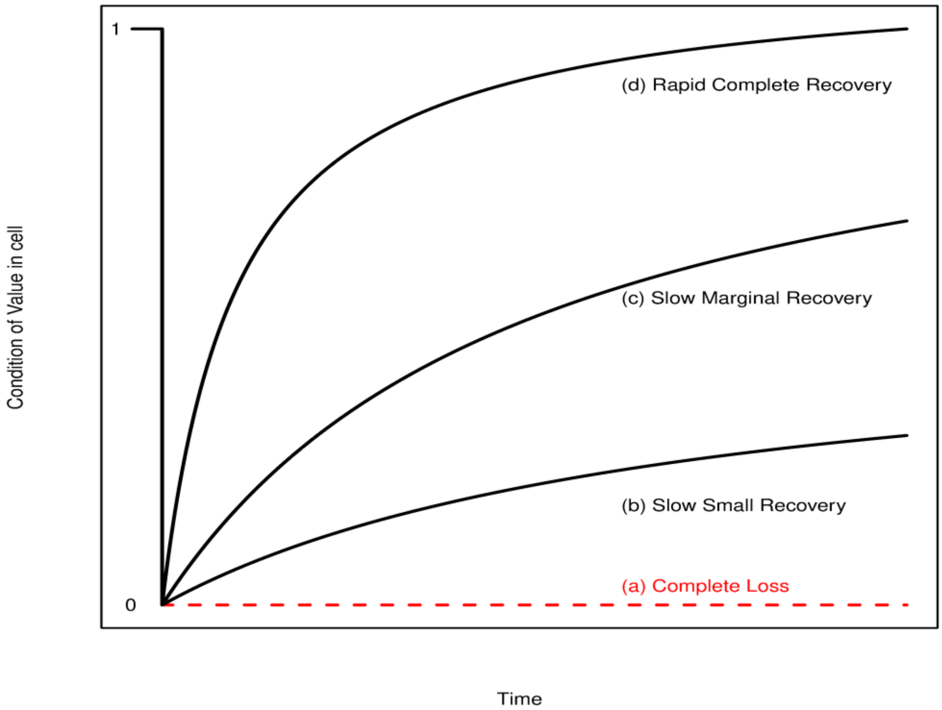

Figure 2: Potential Impact Scenarios at a single grid cell location within a mining lease area

There are two material decisions, what is $Limit$ and what is N. These decisions will need to be made by the ISA as the regulator. The $Limit$ could be between 0 (*i.e.*, no allowed mining) and 1 (*i.e.*, complete loss of all ecosystem components N). Leduc *et al*. (2024) provides guidance on how this limit can be derived and the consideration that needs to be given to the properties of the $Receptor$. This calculation assumes that there are no outcome controls and does not trust that input controls will be effective—it is a *provisionally pessimistic assumption*. To illustrate this approach, and how it might differ to other scenarios, we construct a hypothetical mining operation where there are 100 mining grid cells where one cell is mined per unit of time (Fig. 3a). We arbitrarily set the $Limit$ to 0.5 and assume that whenever a cell is mined or impacted by mining operations everything within it is lost. After 50 time units, the $Limit$ has been reached and operations must stop ((Fig. 3b)). Where there are multiple receptors, multiple impact scenarios and multiple limits would need to be tracked.

2.5 Step 6: Adaptive management

If an adaptive management program is adopted with monitoring and outcome controls (*i.e.*, $Limits$) identified for high risk ecosystem components (*i.e.*, those addressed in step 4), then an adaptive management approach can be taken. This approach will explicitly account for varying values of $S(g, p, d, j, \dots) I(p, d, j, \dots) E(p, d, j, \dots)$ and monitor the status of R to ensure that the limit is not reached.

For a single grid cell location j (*i.e.*, impacted by mining once with extend E_p), the change through time will be

$$R_{\{j,t\}} = \frac{N_{\{j\}} - L_{\{j\}} + Rec_{\{j,t\}}}{N_{\{j\}}} \tag{7}$$

We assume that at some point in time that direct impacts from mining activities will cease. There is then the potential that there may be some form of demonstrated species, habitat and ecosystems recovery. To illustrate this recovery we use a Michaelis–Menton equation to describe how any mine impacted cell would recover post mining. The terms are:

$$Rec_{j,t} = \frac{\beta_1 * t}{\beta_2 + t}$$

where:

β_1 = the maximum recovery possible over $E(p, d, j, ...)$, and

β_2 = the time to 50% recovery.

t = time since impact from pressure stopped.

Other forms of recovery could equally be used (*e.g.*, logistic, Ricker), but Michelis–Menton has easy to describe terms.

Operation can continue while

$$Limit < 1 - \frac{\Sigma_{\{j=1\}}^{\{j=m\}} (L_{\{j\}})}{\Sigma_{\{i=1\}}^{\{i=100\}} N_{\{i\}}} + \frac{\Sigma_{\{j=1\}}^{\{j=m\}} (Rec_{\{j,t\}})}{\Sigma_{\{i=1\}}^{\{i=100\}} N_{\{i\}}} \quad (8)$$

or

$$Limit < 1 - \frac{loss\ due\ to\ mining}{total\ abundance\ of\ the\ receptor} + \frac{\text{Recovery since mining}}{total\ abundance\ of\ the\ receptor}$$

Here we explicitly allow for the possibility of something other than complete loss of ecosystem components from initial impact, with recovery explicitly allowed for and that operations may not completely remove all ecosystem components or processes. These changes in assumptions need to be demonstrated through initial and on-going monitoring to show how much initial loss there is and what degree of recovery, if any, there is. The extension of mining operations beyond what is allowed under the complete-loss scenario is determined by the amount of initial loss when impacted by mining and post-mining recovery at each site. Crucially, operations can be adjusted if the proponent cannot demonstrate that the loss from current operations and recovery from past operations are not as expected to ensure that the $Limit$ is never reached.

Because mine operations occur sequentially through time and space, this allows for an initial start assuming a provisionally pessimistic loss of 100%, with on-going monitoring to show actual levels of loss and recovery through time. Figure 3 provides three general examples of how rates of recovery could play out in the management of mining operations over time. If, for example, monitoring data provides evidence of rapid and complete (Fig. 2 line d) receptor recovery, then it is possible that mining could continue over the entirety of N (Fig. 3b) and that the $Limit$ would never be reached (Fig. 3c). Conversely, if there is slow and marginal recovery, then mining could continue for a discrete period of time (Fig. 3e) before the $Limit$ is reached (Fig. 3f). If, however, there is slow and small recovery, then this would make very little difference to the time operations are allowed to continue compared with a complete loss scenario, and operations could only be extended for a slight increase in time (Fig. 3g) before the $Limit$ is reached (Fig. 3h).

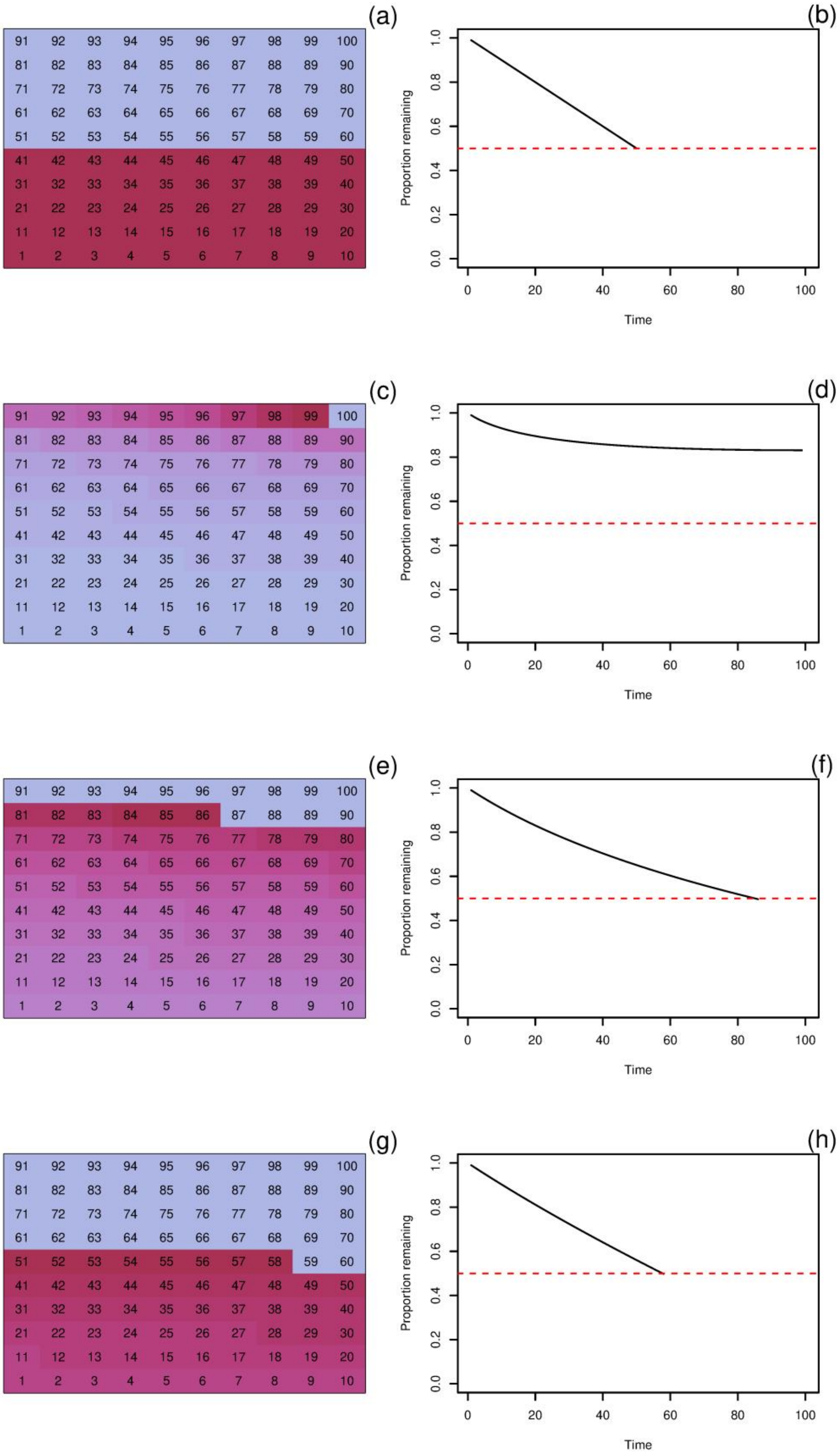

Figure 3: Example scenarios for hypothetical deep-sea mining operations.
For panels a, c, e and g, blue represents grid cells not impacted by mining operations and red indicates impacted areas. The shading between red to blue indicates the degree of recovery. For panels b, d, f and h, the red line shows the example limit and the black line shows the total proportional loss of *N* over the entire assessment area. Panels a and b show the outcome for complete loss (Fig. 2a); Panels c and d show the outcome for rapid complete recovery (Fig. 2d); Panels e and f show the outcome for slow marginal recovery (Fig. 2c); and Panels g and h show the outcome for slow small recovery (Fig. 2b).

3 Discussion

Like driving a car in a new country, effectively regulated deep-sea mining will need to rely on both input controls (*e.g.*, light, noise, sediment) and outcome controls (*e.g.*, status and trend of key receptors), and if it is to commence, it will need to meet the dual objectives of not causing serious harm while having a path for commercial-scale operations. We have attempted to describe a process that could be used to begin operations while giving clear limits that can be determined by the regulator. It is reliant on a provisionally pessimistic approach where there is an assumption of complete loss of ecosystem components or processes and provides the incentive to modify or relax this assumption through on-going monitoring and assessment.

3.1 Operations in an area of high uncertainty

Deep-sea mining operations take place in highly uncertain environments that are difficult to observe, and a provisional pessimistic assumption allows for operations begin even when there is extreme uncertainty about the impact and effects to the environment. Making an assumption of complete loss of receptors at the beginning of operations allows simplifying assumptions that will make it easier for regulators to define a $Limit$ to high risk activities. Furthermore, allowing proponents to demonstrate that their activities do not cause complete loss of receptors can incentivise monitoring programs. Well-designed and sustained monitoring will reduce the uncertainty of effects from mining operations through time, allowing for better estimation of the effects of deep-sea mining at lease and regional spatial scales. However, this approach requires two key decisions to be made: 1) what is the total spatial extent of the area of the receptor, 2) what is the limit.

3.2 Spatial extent of the receptor

The total spatial extent of the receptor (*i.e*., as represented as the grid in our example $\Sigma_{\{\mathrm{i}=1\}}^{\{i=100\}} N_{\{i\}}$) will be a key determinant of the scale of operations allowed and its definition a key requirement to operationalise our approach. The guidance provided in Leduc *et al*. (2024) can provide guidance on the likely extent of the receptor, but ultimately this will need to be based on evidence. It has not been established how broadly deep-sea species that comprise ecosystems in the CCZ are distributed but may require information on the distribution of a large number of species and functional groups.

An important consideration in determining both the extent of the receptor and the limit of harm is understanding the distribution of ecosystem components. It is common to observe a single individual of a species in a survey (singletons) in many marine ecosystems, and especially common in deep sea species (Foster and Dunstan 2010, Dunstan *et al*. 2012). One interpretation of the long tail of species abundance is that there are many rare species in these ecosystems. Singletons (and other species with few occurrences), however, are often a function of sampling effort, both in terms of total sampling effort and species missed due to gear and sampling limitations. Zero-inflated distributions are compound distribution of the likelihood of species being present at a location and species being sampled by gear and will give the impression that everything is rare. The ability to distinguish between rare and poorly-sampled species is difficult, but latent class models (as in Woolley *et al*. 2025) are generally better than single species models in predicting rare-species distributions (Hui *et al.* 2013).

- If the extent of the receptor is larger than a lease area (*i.e*., regional), then operations of multiple leases will contribute to the overall limit. This could involve considering the cumulative effects from multiple operations.
- If the extent of the receptor is at the lease scale, then operations are isolated from other operations. This scale assumes that there is no within-lease variations in ecosystem components/processes and mining operations are identical across the lease area.
- If the extent of the receptor is smaller than a lease scale, then operations within a lease will need to be informed by data with each ecosystem component or process assessed independently.

3.3 Calculation of the limit

The limit (as in equation 6) is the other key decision to be made by the regulator. As noted, this limit can be between 0 (no effect on the receptor) and 1 (all of the receptor removed). A limit of 1 is inconsistent with the agreed goals of the ISA to prevent a significant adverse change in the marine environment (*i.e*., serious harm). If deep-sea mining proceeds, then there must be some level of harm that is allowed, deciding this level will be a future challenge. Leduc *et al*. (2024) gives clear guidance that the level of serious harm could be reached when the environmental effects include the loss of a large amount of a habitat (extent); or are irreversible, lasting for more than several generations (*i.e.*, generation time of affected organisms), or occur more than once per generation (duration or frequency); and lead to substantial loss of populations, species, communities, habitats or ecosystem function (magnitude). This value can be adjusted as information on the ability of a population to replace individuals lost following mining and whether mining leads to a loss of species richness, habitat, community or communities, or ecosystem functions and a substantial reduction in biomass or local extinction of key species. It is worth noting that Leduc *et al*. (2024) suggested a threshold for where detectable harm becomes significant harm and a limit for when significant harm becomes serious harm. We have concentrated on the limit, but note that the threshold for harm (Leduc *et al.* 2024) could be estimated in a similar way, but with a value closer to 0 than the limit. Operations that are close to the threshold for harm may be used to trigger increased monitoring to ensure that operations never come close to causing serious harm.

3.4 Conclusion

This report has laid out the process to establish limits to deep-sea mining operations that begins with a provisionally pessimistic approach that can be updated through an adaptive monitoring program that is informed by on-going monitoring. The approach provides the regulator with two key decisions: (1) what is the total extent of the receptor , and (2) how much loss of the receptor will cause serious harm if complete loss is assumed. This novel analytical framework provides proponents the opportunity to demonstrate that loss is not complete through an on-going monitoring program and potentially extend mine operations through on-going monitoring.

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