Qualitative Mathematical Models for Assessing Cumulative Impacts on Ecosystems of the Mid-Atlantic Ridge from Future Exploitation of Polymetallic Sulphides

Executive Summary

The International Seabed Authority (ISA), in collaboration with the Atlantic REMP Project (funded by the European Union) and the Government of Portugal, convened the Workshop on the Regional Environmental Management Plan (REMP) for the Area of the Northern Mid-Atlantic Ridge (MAR), at the University of Évora, Évora, Portugal, from 25-29 November 2019. This workshop focused on compiling and synthesizing scientific data and information to support the application of area-based management tools and adaptive management as well as addressing cumulative impacts, which will provide input to the identification of potential environmental management measures for the development of the REMP in the region.

A qualitative mathematical modelling approach based on expert knowledge was introduced to address cumulative impacts on MAR ecosystems from pressures associated with potential polymetallic sulphide (PMS) exploitation activities and other human and natural stressors in the region. Modelling exercises performed during the Évora workshop were constrained by: a) the limited time available; b) the narrow range of expertise represented at the workshop; and c) the lack of access to information to support the model descriptions, assumptions and outcomes.

Two informal working groups were subsequently established to further develop qualitative mathematical models, through a series of video conference calls facilitated by the Marine Biodiversity Risk & Management team of the Commonwealth Scientific and Industrial Research Organisation (CSIRO), the ISA Secretariat, and the Atlantic REMP Project, between March and June 2020. This report presents an overview of the two ecosystem models, one including the pelagic environment and non-hydrothermal sediment habitats and another focusing on hydrothermally active habitats. Details on the methodology for qualitative mathematical modelling, as well as descriptions of each model's assumptions, scenarios and outcomes are provided in Annex II-IV. The report also provides a summary of considerations for future cumulative impact modelling to inform regional environmental management.

The work presented in this report is the first step towards the development of a comprehensive conceptual framework for assessing potential impacts from future PMS exploitation activities, as well as multi-sector impacts, at a regional scale. The current models provide a systematic ecosystem-based approach to identify pressures that are likely to have significant ecosystem impacts, both individually and cumulatively. This information can be used to prioritize mitigation or avoidance measures to reduce the impacts of key pressures, reducing the overall cumulative impact.

The current modelling exercise focused on the potential cumulative impacts arising from exploitation of a single PMS deposit. Engagement with contractors, economic geologists, and seabed mining engineers will be needed to elucidate the potential temporal and spatial scales of impacts from future

PMS exploitation activities, as well as to draw further realistic scenarios of mining operations, including mining technology. Engaging with other ocean industry sectors in future modelling exercises would also facilitate greater understanding of cumulative impacts arising from multiple human activities. For ecosystem models to progress towards a quantitative approach that may support the establishment of thresholds for acceptable impacts at local and regional scales, more quantitative information is needed on the ecosystem components and their responses to the identified pressures, as well as information on the geographic distribution of the ecosystems and sites targeted for future PMS exploitation.

1. Background

The International Seabed Authority (ISA), in collaboration with the Atlantic REMP Project (funded by the European Union) and the Government of Portugal, convened the Workshop on Regional Environmental Management Plan (REMP) for the Area of the Northern Mid-Atlantic Ridge (MAR), at the University of Évora, Évora, Portugal, from 25-29 November 2019. This workshop focused on compiling and synthesizing scientific data and information to support the application of area-based management tools and adaptive management as well as addressing cumulative impacts, which will then provide inputs to the identification of potential environmental management measures for the development of REMPs. The current state of knowledge and data available were summarized in two background documents prepared for the workshop, including a report on Regional Environmental Assessment[1] and a Data Report[2]. The outcomes of the expert discussions and scientific analysis were compiled in the workshop report[3].

A qualitative mathematical modelling approach based on expert knowledge was introduced to address cumulative impacts on MAR ecosystems from pressures associated with potential polymetallic sulphide (PMS) exploitation activities and other human and natural stressors in the region (See Annex VII of the workshop report). The preliminary modelling work undertaken during the Évora workshop demonstrated the potential utility of the qualitative mathematical models as a systematic approach to identify risks, as well as research and monitoring needs, and to inform adaptive management measures. However, modelling exercises performed during the Évora workshop were constrained by the time available during the workshop; the range of expertise available from the workshop participants; and the ability to access information to support the model descriptions, assumptions and outcomes.

The workshop participants agreed that follow-up work to the Évora modelling exercise would provide the opportunity to develop qualitative mathematical models that could be better supported through drawing on additional scientific expertise and referring to the best available scientific literature. This follow-up work would also allow for testing and validating model outputs, and for further interpretation of the model outcomes. Participants considered a series of pre-defined scenarios, which were adapted to be more relevant to the different ecosystem models.

2. Post-Workshop Informal Working Groups

The modelling work following the Évora workshop was restricted to two informal working groups each addressing different habitats. Group I included the pelagic environment and non-hydrothermal sediment habitats; and group II focused on hydrothermally active habitats. The hydrothermally inactive and non-hydrothermal hard substrata habitats (discussed in Évora) were not included in the follow-up modelling

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[1] https://ran-s3.s3.amazonaws.com/isa.org.jm/s3fs-public/files/documents/rea-feb2020-reduc.pdf

[2] https://ran-s3.s3.amazonaws.com/isa.org.jm/s3fs-public/files/documents/data_report-feb2020-reduc.pdf

[3] https://ran-s3.s3.amazonaws.com/isa.org.jm/s3fs-public/files/documents/evora_workshop.pdf

work due to practical limitations, including the current lack of knowledge on the ecology of hydrothermally inactive habitats on the northern MAR.

Participants from the Évora workshop were contacted and asked to participate in the follow-up modelling exercise, on a voluntary, informal basis. To address some of the knowledge gaps identified during the Évora workshop, where feasible, additional experts were invited to join the informal working groups. A full list of the participants in the two informal working groups, alongside their relevant expertise, is provided in **Annex I**.

The modelling exercise was conducted through a series of remote video conference calls, held between March and June 2020, and facilitated by the Marine Biodiversity Risk & Management team of the Commonwealth Scientific and Industrial Research Organisation (CSIRO), the ISA Secretariat, and the Atlantic REMP Project. During these remote meetings, the CSIRO team used expert elicitation to build qualitative mathematical ecosystem models based on the participants' knowledge of the MAR ecosystem. These models were drawn and displayed to participants in real time, with participant feedback both during and between the meetings enabling the refinement of these models.

3. Qualitative models for Assessing Cumulative Impacts

The concept of a 'cumulative impact' can have different meanings according to the setting and context in which it is used. For the purpose of the modelling exercise conducted by the informal working groups, the following two levels of cumulative impacts were considered:

1) where a single pressure can have a cumulative impact across multiple ecosystem components in the model. In this case, the impact from an initial direct pressure on one ecosystem component was propagated to other ecosystem components through the web of interactions established in the model, showing the expected changes to parts of the ecosystem that are not directly impacted.
2) where multiple individual pressures were combined into perturbation scenarios. The direct effect of these combined pressures on individual ecosystem components was again propagated to other components through the model, allowing calculation of cumulative impacts to the ecosystem.

Following the establishment of separate ecosystem models for each of the groups, participants were asked to consider the potential impacts (pressures) that future exploitation activities for PMS on the northern MAR may have on the ecosystem components identified in the models. The cumulative impacts assessed through the modelling exercise were qualitative, with experts assigning the direction (positive or negative) of ecosystem component response to pressures. This modelling approach enables the identification of which pressures are most likely to cause the largest change, either individually or when combined. Further details on the methodology for the modelling exercise are provided in **Annex II**.

3.1 Model Assumptions and Scenarios

Participants considered a series of pre-defined scenarios, which were adapted to be more relevant to the different ecosystem models. For all cumulative impact scenarios, it was assumed that the habitat at the mine site itself would be completely removed, and that perturbations to ecosystem processes would only be modelled beyond this immediate footprint. The impact scenarios do not apply strict temporal and spatial boundaries, as the precise spatiotemporal scales of potential impacts from PMS exploitation are not yet known. However, explanation of the temporal and spatial scales over which impacts on model linkages and processes were considered is provided in the accompanying descriptions for each of the models in **Annex III** and **Annex IV.**

Pelagic and non-hydrothermal sediment ecosystem model:
For the pelagic environment and non-hydrothermal sediments ecosystem model, it was assumed that exploitation of buried PMS deposits would lead to the removal of sediment overburden, which may be placed in neighbouring benthic environments. Two potential PMS exploitation scenarios were considered regarding the depth at which return water would be placed, to reflect the two extremes of potential return water discharge scenarios. Scenario one placed the return water in the surface environment (0-200m depth); scenario two placed the return water near the seafloor, within or as close to the benthic environment (seafloor to 50 m above seafloor) as possible. For the pelagic environment and non-hydrothermal sediments ecosystem model, consideration was also given to four potential climate change scenarios. These climate change scenarios considered the impact that increasing ocean temperature may have on primary production in the surface waters and the quality of food that falls down to the deep pelagic and benthic environment. Detailed descriptions of these scenarios and model assumptions are provided in **Annex III**.

Hydrothermally active habitat ecosystem model:
For the hydrothermally active ecosystem model, three potential PMS exploitation scenarios were considered. Scenario one entailed the complete removal of one hydrothermally active PMS deposit within a vent field and detailed the potential impacts on hydrothermally active habitat within the same vent field. Scenario two also entailed the complete removal of one hydrothermally active PMS deposit within a vent field but considered the potential impacts on hydrothermally active habitat within a different vent field. Scenario three involved the removal of a single hydrothermally inactive PMS deposit and considered the potential impacts on hydrothermally active habitat within the same vent field. Detailed descriptions of these scenarios and model assumptions are provided in **Annex IV**.

3.2 Model Outcomes

The qualitative mathematical ecosystem models identified the individual pressures and combinations of pressures that were predicted to have the most negative impact on pelagic and non-hydrothermal sediment habitats, and on hydrothermally active habitats on the MAR. The models also identified the individual ecosystem components that were predicted to have the most negative responses to individual pressures or combinations of pressures under the perturbation scenarios.

Main outcomes for the pelagic and non-hydrothermal sediment ecosystem model:

- The predicted responses of ecosystem components to individual PMS exploitation pressures depended on where the pressures originated (surface, midwater or benthic) and which part of the ecosystem the components came from (surface pelagic, deep pelagic, or demersal and benthic).
- The discharge of high turbidity return water at the surface, and the noise from pumping activities using vertical pipes in the water column, were the two individual PMS exploitation pressures predicted to elicit the greatest number of negative responses from the biological components of the ecosystem model.
- When potential PMS exploitation pressures were considered together in perturbation scenarios, most of the biological components of the ecosystem were predicted to have negative responses to the combined effects of exploitation activities. The perturbation scenarios where return water was

discharged at the surface were predicted to have a greater overall negative effect on the ecosystem than scenarios where return water was discharged near the seafloor.

- The predicted response to individual climate change pressures depended on the effect that increased temperature had on the primary production of phytoplankton or on the food quality of particulate organic matter (POM). Where there was a negative effect on primary productivity the predicted ecosystem response was always negative. Where there was a negative effect on the food quality of POM, there was more uncertainty in predicted ecosystem responses.
- When potential climate change pressures were considered together in perturbation scenarios, where climate change had the effect of decreasing primary production of phytoplankton, ecosystem components were generally predicted to have negative responses. There was more uncertainty in predicted ecosystem response where a decrease in primary productivity was combined with improved food quality of POM.

Main outcomes for the hydrothermally active habitat ecosystem model:

- The reduction in subsurface connectivity of fluid flow within the hydrothermal vent field was the individual PMS exploitation pressure predicted to elicit the greatest number of negative responses from the physical and biological components of the ecosystem model. For many of the other individual exploitation pressures considered, the biological components exhibited a high degree of uncertainty in the type of predicted response to these pressures. More information on the nature of PMS exploitation pressures, and the biological response to these pressures, would be needed to reduce uncertainty in predicted model outcomes.
- When potential PMS exploitation pressures were considered together in perturbation scenarios, the perturbation scenarios that reduced subsurface connectivity of fluid flow within the vent field were predicted to have the greatest overall negative effect on the hydrothermally active ecosystem. The ecosystem components had the same predicted response to reduced subsurface connectivity when either a hydrothermally active or a hydrothermally inactive PMS deposit was exploited.
- The perturbation scenario that was the least negative overall for the unmined hydrothermally active habitat was where exploitation occurred at a hydrothermally active PMS deposit in a different vent field. Where exploitation occurred within the same vent field, fewer negative responses from ecosystem components were predicted where subsurface connectivity was not impacted.

4. Considerations for Future Cumulative Impact Modelling to Inform Regional Environmental Management

The qualitative mathematical modelling approach undertaken here is the first step towards the development of a comprehensive conceptual framework for assessing potential impacts from future PMS exploitation activities, as well as multi-sector impacts, at a regional scale. By elucidating the ecological processes through which future PMS exploitation activities may impact the marine ecosystems of the northern MAR, this ecosystem-based approach allows for the identification of parts of the ecosystems that are the best indicators of ecosystem state for any particular set of pressures. The current models can be used to identify pressures that are likely to have significant ecosystem impacts, both individually and cumulatively, and both within and between the pelagic, benthic and vent ecosystems assessed herein. This information can be used to prioritise mitigation or avoidance measures to reduce the impacts of key pressures, reducing the overall cumulative impact.

For both habitat groups, there was uncertainty on the potential temporal and spatial scales of impacts from future PMS exploitation activities, which may be addressed through engaging with contractors, economic geologists, and seabed mining engineers. There were also some specific areas of expertise that would be needed to refine the linkages between components in the ecosystem models. For the pelagic and non-hydrothermal sediments model, future modelling exercises would benefit from involving phytoplankton, zooplankton and climate change experts. For the hydrothermally active model, specific expertise on the hydrology of hydrothermal systems would improve the ability to model potential changes in hydrothermal flow within a vent field that may arise from future PMS exploitation activities. In addition, further models would need to be developed for the remaining key habitats, such as hydrothermally inactive and non-hydrothermal hard substrata habitats, to undertake a comprehensive and robust ecosystem-based model for cumulative impact assessment in the northern MAR region.

The current modelling exercise focused on the potential cumulative impacts arising from exploitation of a single PMS deposit. For ecosystem models to progress towards a quantitative approach that may support the establishment of thresholds for acceptable impacts at local and regional scales, more quantitative information would be needed on the ecosystem components and their responses to the identified pressures, as well as information on the geographic distribution of the ecosystems and sites targeted for future PMS exploitation. Further quantitative and/or statistical modelling would be required to predict the magnitude of cumulative impacts deriving from exploitation activities at multiple PMS deposits or multiple ocean industry sectors within the region, such as bottom contact fisheries, submarine cables or shipping. Engaging with these sectors in future modelling exercises could facilitate greater understanding of cumulative impacts arising from multiple human activities.

Annex I Composition of the Informal Working Groups

Name	Institution and State	E-Mail	Scientific Expertise
Hydrothermally active habitat experts			
Malcolm Clark§	National Institute of Water and Atmospheric Research (NIWA), New Zealand	malcolm.clark@niwa.co.nz	Community structure and ecology, mining impacts
Ana Colaço	Institute of Marine Research (IMAR) – Azores, Portugal	maria.aa.colaco@uac.pt	Trophic relationships, connectivity, community structure and ecology, mining impacts
Sabine Gollner	Royal Netherlands Institute for Sea Research (NIOZ) – The Netherlands	sabine.gollner@nioz.nl	Community structure and ecology, connectivity, mining impacts
Ashley Rowden§	NIWA & Victoria University of Wellington – New Zealand	ashley.rowden@vuw.ac.nz ashley.rowden@vuw.ac.nz	Community structure and ecology, mining impacts
Tanja Stratmann§	NIOZ – The Netherlands	tanja.stratmann@nioz.nl	Trophic relationships, mathematical modelling
Cindy Van Dover	Duke University Division of Marine Science and Conservation – NC, U.S.A.	clv3@duke.edu	Trophic relationships, connectivity, community structure and ecology
Pelagic environment and non-hydrothermal sediments experts			
Teresa Amaro	Interdisciplinary Centre of Marine and Environmental Research (CIMAR) – Portugal	amaro.teresa@gmail.com	Benthic biota: trophic relationships
Jacqueline Eggleton	Cefas Lowestoft Laboratory – U.K.	jacqueline.eggleton@cefas.co.uk	Benthic biota: community structure and ecology
Livia Ermakova	Ministry of Natural Resources and Environment of the Russian Federation – Russia	livia77@inbox.ru	Physical oceanography: currents, mining impacts
Gordon Paterson	Natural History Museum of London – U.K.	g.paterson@nhm.ac.uk	Benthic biota: community structure and ecology, mining impacts
Imants Priede	University of Aberdeen – U.K.	i.g.priede@abdn.ac.uk	Pelagic biota: trophic relationships, community structure and ecology
Facilitators			
Rachel Boschen-Rose	Seascape Consultants, Atlantic REMP Project Secretariat – U.K.	rachel.boschen-rose@seascapeconsultants.co.uk	Benthic ecology, mining impacts
Jeffrey Dambacher§	Commonwealth Scientific and Industrial Research Organisation (CSIRO) – Australia	jeffrey.dambacher@csiro.au	Qualitative mathematical modelling
Piers Dunstan§	CSIRO – Australia	piers.dunstan@csiro.au	Qualitative mathematical modelling
Luciana Genio	ISA Secretariat – Jamaica	lgenio@isa.org.jm	Benthic ecology
Skipton Woolley	CSIRO – Australia	skip.woolley@csiro.au	Qualitative mathematical modelling

§ The individual did not participate in the Évora workshop

Annex II Methodology for Qualitative Mathematical Modelling for Assessing Cumulative Impacts

Qualitative mathematical models represent a working hypothesis about how an ecosystem works. They should: identify important components and processes in the system; document assumptions about how these components and processes are related; identify the linkages between these components, processes and anthropogenic pressures, and also identify knowledge gaps or other sources of uncertainty. These models are useful in identifying the potential cumulative impacts of pressures on ecosystem components and the best indicators for those impacts. They can be applied to a very broad range of ecosystems from coastal marine systems to deep-sea systems (Dunstan et al 2020).

Steps or tasks in constructing qualitative mathematical models include identifying the bounds of the system of interest; determining key model components, subsystems, and interactions; identifying natural and anthropogenic stressors (pressures); describing relationships of stressors, ecological factors, and responses; and identifying clear knowledge gaps in the system.

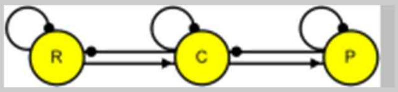
Qualitative mathematical models need to portray the ecological system at a level of resolution that is useful to the purposes of the risk assessment, striking a balance between simplicity and complexity. They should not seek to represent the entire system with myriad components and processes; rather the focus is on the dominant processes and feedbacks that sustain and regulate the main components of interest, along with potential anthropogenic pressures and natural stressors relevant to the ecosystem (*sensu* Gross 2003; Dambacher et al., 2009).

A qualitative mathematical model is implemented through a partial specification of the system. In a partially specified system, only the qualitative nature of the relationships between variables is specified. Under this approach, the effect of one variable on another can be specified only through the sign of its effect, e.g. positive (+), negative (-) or no (0) effect. Qualitative modelling is based on representing the qualitative nature of the relationships shared between system components and variables (Puccia & Levins 1991). This approach sacrifices precision in model details and predictions but gains a causal understanding of a system that is pertinent to a broad range of contexts and applications (Justus 2005; 2006).

The method of qualitative mathematical modelling is based on the analysis of system structure using signed directed graphs (hereafter signed digraphs) (Puccia & Levins 1985). A signed digraph is a graphical representation of variables and their interactions, where the nodes or vertices of the graph represent the system variables, and the graph edges or links represent both the sign and the direction of the direct effect of one variable on another, i.e. a positive (+), a negative (-) or a null (0) effect. Signed digraph models of ecosystems commonly include trophic interactions; for example, in a predator-prey interaction the positive benefit to a predator of consuming a prey represents a rate of birth, and the negative effect to the prey represents a rate of mortality (**Box 1**).

Box 1. Qualitative mathematical models and their analysis

The below signed digraph is a straight-chain system with a basal resource (R), consumer (C) and predator (P). There are two predator-prey relationships, where the predator receives a positive direct effect (*i.e.*, nutrition, shown as link ending in an arrow (→)), and the prey receives a negative direct effect (*i.e.*, mortality, shown as link ending in a filled circle (●—included also are self-effects, such as density dependent growth.



Prediction of perturbation response. One can predict the direction of change in each variable (*i.e.*, increase, decrease, no change) due to a sustained input or pressure to the system. Consider a pressure on the system in the way of food supplementation to the predator that increases its reproductive capacity. The predicted response of C is determined by the sign of the link leading from P to C, which is negative (denoted P —● C). The predicted response of R will be positive because there are two negative links in the path from P to R (P —● C —● R), and their sign product is positive (*i.e.*, - x - = +). In this system, there is complete sign determinacy for all response predictions, as there are not multiple pathways between variables with opposite signs.

Based on the qualitative structure of a system detailed in a signed digraph, one can assess the scope or potential for a system to be stable, and if it is stable, then how it will respond to a perturbation that shifts the system to a new equilibrium. Under a sudden and small pulse perturbation, a stable system will return to its former equilibrium but if the system is unstable, then it will either be attracted to a new equilibrium in which abundances or values of the variables are shifted to different levels, or the system may even collapse, leading to the extinction of one or more components.

A sustained change in a system parameter, or a press perturbation, will displace the system to a new equilibrium point. This system displacement occurs through a change in the growth rate of one or more input variables, which then creates a series of direct and indirect effects that are transmitted to other variables through the system's network of interactions. Based on the structure of these interactions, one can predict changes in the equilibrium abundances and rate of turnover in model variables. Obtaining a clear description of the interaction structure based on the direct effects of the system enables disentangling complex relationships between variables that can be key when evaluating system response to perturbations. Once the structure of a signed digraph model is defined, it can be analysed to determine predictions for perturbation response (Puccia & Levins 1985; Dambacher et al., 2002; 2003). These qualitative predictions can be assessed to determine their relative potential for sign determinacy. A model variable that receives only positive direct and indirect effects from a perturbation can only have a positive response, if a variable only receives negative effects it can only have a negative response. Where a variable receives both positive and negative effects, then its response is qualitatively ambiguous, but here a probability for the response sign can be determined based on the relative balance of positive and negative effects involved. Dambacher et al. (2002) and Hosack et al. (2008) developed a method to assign probabilities of sign determinacy based on results of numerical simulations of signed digraph models. For instance, a variable that receives three positive and one negative effect from a pressure will, in computer simulations, have a positive response greater than 90 percent of the time. Here we use this approach to distinguish completely determined response predictions (i.e., sign determinacy equal to 100%) from those that are ambiguous, and further identify those with a relatively high probability of sign determinacy set at ≥80%, and those with a low probability of sign determinacy (<80%).

Qualitative mathematical models can be created almost entirely from the description of processes and narratives. The scope and bounds of the studied system or problem is first defined, and the components of interest are then identified. Variables are chosen with respect to the research or management problem that motivated the formulation of the model. In establishing the relationships between variables, one asks 'what is the direct influence of one variable on another', and 'what else in the system determines the creation or destruction of a variable'. In addition to biological variables, model components can also include physical and environmental factors as well as social and economic processes.

Workshops with domain experts and literature reviews are a primary source of system description. Additionally, symbolic analysis of process-based equations can help elucidate interactions that are not clearly defined through a verbal description, as frequently is the case for self-damping of a variable or for modified interactions (Dambacher & Ramos-Jiliberto 2007).

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Annex III Qualitative Mathematical Models for Assessing Cumulative Impacts from Future Exploitation of Polymetallic Sulphides on the Pelagic and Non-Hydrothermal Sediment Habitats of the Mid-Atlantic Ridge

Overview

- A qualitative mathematical ecosystem model for pelagic and non-hydrothermal sediment habitats on the Mid-Atlantic Ridge (MAR) was created through expert elicitation. Potential pressures on this ecosystem model were described for future mineral exploitation activities and climate change.
- Two polymetallic sulphide (PMS) exploitation scenarios were considered to test the applicability of the modelling approach. Each scenario involved the removal of sediment overburden; disaggregation of PMS on the seafloor and pumping to the surface; dewatering at the surface; and discharge of the return water from surface processing. The two exploitation scenarios separately considered discharge of return water at the surface, or near the seafloor.
- A suite of 13 pressure effects from climate change and exploitation activities were assessed for the 18 ecosystem components in the model.
- Individual pressures from PMS exploitation activities resulted in a range of predicted responses in ecosystem components, depending on where the pressures originated (surface, midwater or benthic) and which part of the ecosystem the components came from (surface pelagic, deep pelagic, or demersal and benthic). The two individual exploitation pressures with the greatest number of predicted negative responses across all ecosystem components in the model were the discharge of high turbidity return water at the surface and the noise from pumping activities using vertical pipes in the water column.
- The response to individual climate change pressures depended on the effect that increased temperature had on primary production of phytoplankton or on the food quality of particulate organic matter (POM). Where there was a negative effect on primary productivity, negative responses were predicted for ecosystem components. Conversely, where there was a positive effect on primary productivity, positive responses were predicted. Where there was a negative effect on the food quality of POM, predicted responses for ecosystem components were negative, uncertain or no response. Positive effects on the food quality of POM elicited positive and uncertain predicted responses or no predicted response.
- When potential exploitation pressures were considered together in perturbation scenarios, most components of the pelagic and non-hydrothermal sediment ecosystem were predicted to have a negative response to the combined effects of exploitation activities. The perturbation combinations where return water was discharged at the surface had a greater overall negative effect on ecosystem components than perturbation combinations where return water was discharged near the seafloor.
- When climate change pressures were considered together in perturbation scenarios, where climate change had the effect of decreasing primary productivity of phytoplankton, ecosystem components were generally predicted to have negative responses. There was more uncertainty in the predicted response of ecosystem components where a decrease in primary productivity was combined with an improved food quality of POM.

Background to the modelling exercise

The purpose of this modelling exercise was to describe potential cumulative impacts from the exploitation of polymetallic sulphide (PMS) deposits created through hydrothermal activity along the Mid-Atlantic Ridge (MAR).

The concept of a ‘cumulative impact’ can have different meanings according to the setting and context in which it is used. For the purpose of the modelling exercise, two levels of cumulative impacts were considered. The first was where a single pressure can have a cumulative impact across multiple ecosystem components in the model. In this case, the impact from the initial direct pressure on one ecosystem component was propagated to other ecosystem components through the web of interactions established in the model. The second level of cumulative impact considered was where multiple individual pressures were combined into perturbation scenarios. The direct effect of these cumulative impacts on individual ecosystem components was again propagated to other components through the model. Cumulative impacts relating to the exploitation activities of multiple contractors or multiple ocean industry sectors within a region were not explored in this modelling exercise.

The cumulative impacts assessed through the modelling exercise were qualitative, with experts assigning the direction (positive or negative) of ecosystem component response to pressures. There was insufficient information available to put weights or values on ecosystem component responses, which would be needed to develop quantitative models. Instead, qualitative mathematical models encoded as signed directed graphs (signed digraphs) were used to describe how key linkages amongst ecosystem components of the pelagic and non-hydrothermal sediment ecosystem could be impacted under several ecosystem structure and PMS exploitation or climate change scenarios. Signed digraphs provided a qualitative depiction of variables in the ecosystem and the structure of the relationships by which they are linked. Positive effects and processes that cause the increase of a variable (e.g., a rate of reproduction or a rate of addition) were depicted by a link ending in an arrow; negative effects (e.g., a rate of mortality or a rate of removal) were shown by links ending in a filled circle.

The construction of the model began by defining a focus based on the operational scale of exploitation activities with respect to the ecosystem associated with pelagic and non-hydrothermal sediment habitats on the MAR. Participants were asked to describe essential components, processes and factors associated with this ecosystem, independent of the influence of any potential exploitation activities, with an emphasis on key functional aspects. Following the construction of the ecosystem model, the next step was to describe how different pressures associated with future mineral exploitation activities could possibly affect the ecosystem. These pressures were detailed as positive or negative inputs to specific components of the signed digraph model.

Detailed methodology for the qualitative mathematical modelling approach utilized in this exercise is available in ***Annex II: Methodology for Qualitative Mathematical Modelling for Assessing Cumulative Impacts.***

Pelagic and non-hydrothermal sediment ecosystem model

Definitions of the ecosystem components and representative images of these components are provided in Table 1 and Figure 1 respectively. The signed digraph for the ecosystem model is provided in Figure 2 and detailed information for the individual linkages within the model is provided in Table 2.

The ecosystem model for pelagic and non-hydrothermal sediment habitats was based on biological production in the photic zone contributing to stores of particulate organic matter (POM) that settled to deep pelagic and benthic habitats. Primary and secondary production were represented simply by a single plankton group (including phytoplankton and zooplankton), which was consumed by surface nekton, krill and deep-living myctophids and bristlemouth fish that ascend to the surface at night. Surface nekton was a primary resource for populations of turtles and fish. While fish were depicted as having a controlling influence on the abundance of surface nekton (i.e., a negative effect on surface nekton from predation), this control was not allotted to turtles because their abundance was thought to be too low to have a significant population-level effect. Myctophids and bristlemouth fish were consumed by birds, deep nekton and cephalopods and dragonfish. Cephalopods were a principle resource for cetaceans that can dive to great depths. Most of these components of the pelagic system contributed to stores of POM. The stores of POM sank through the deep layers of the water column where they were principle food resource of deep pelagic plankton, before reaching the seafloor and becoming the food source for epifauna detritivores, infauna detritivores, sessile filter feeders and benthic microbes. This trophic input flowed on to epifauna predators, mobile infauna predators and swimming predators. Only the most important, dominant links were captured by this model.

Some other linkages were discussed but not included in the model. For example, epifauna predators and swimming predators may browse on sessile filter feeders, however this was considered to contribute a very small proportion of the food supply to these groups and the linkage was not included in the model. Some linkages were considered possible and potentially important but uncertain, such as the consumption of POM by sessile filter feeders and the negative effect of cetaceans on cephalopod and dragonfish populations. These uncertain links were indicated by dashed lines in Figure 2 and their inclusion or omission is the basis for construction of two alternative models (Model 1 & Model 2).

A fraction of POM in the pelagic environment is consumed by plankton and hence made available to the mesopelagic food chain. Although Anderson et al. (2019) indicate that only 5% of the diet of myctophids comes via this route (myctophids eating plankton that feed on POM), others have indicated that it could be as high as 42%. One of the big unknowns for pelagic ecology is how much of the POM is recycled in mid water. Consumption of POM by plankton is not included in this model because this link ties a fast subsystem, nutrient recycling, to the slower population-level subsystem. For practical purposes, the relatively rapid dynamics of the nutrient recycling can be omitted where the focus is on the dynamics of the slower subsystem of plankton, invertebrate-and vertebrate population variables. Here, nutrients are sufficiently accounted for in the intrinsic dynamics of the plankton community that is a basal resource for the entire ecosystem. Moreover, the differentiation of recycled nutrients is important only as a matter of quantification and has no influence on the qualitative dynamics assessed here.

Table 1. Description of components included in the Mid-Atlantic Ridge pelagic environment and non-hydrothermal sediment ecosystem model.

Variable name	**Description**
Turtles	Multiple species of air-breathing marine reptiles found in the North Atlantic, including *Dermochelys coriacea* (leatherback turtle), *Chelonia mydas* (green turtle) and *Caretta caretta* (loggerhead turtle). Sea turtles nest on beaches but undertake long oceanic migrations.
Surface nekton	Swimming animals that live in the surface layers that are not fish, turtles, birds or cetaceans. Includes squids, large shrimps and medusas that consume plankton and other prey.
Fish	Numerous species of fish including big game species such as tunas, billfish and sharks.
Birds	Seabirds such as albatrosses, fulmars and petrels that nest in colonies on land and make extensive oceanic migrations. The life span of fulmars often exceeds 50 years and populations are vulnerable to cumulative high seas mortalities.
Plankton	Phytoplankton and Zooplankton are both included in this group, which represents primary and secondary production in the ecosystem.
POM, particulate organic matter	Organic detritus from dead plankton, exudates and animal faeces. These often form aggregates, known as marine snow, that fall towards the seafloor.
Myctophids, bristlemouths and krill	Myctophids and bristlemouths are small (5 cm long) luminescent fishes that ascend to the surface at night to feed on plankton and descend to depth during the day. Krill are shrimps that undertake the same migration. Together, these animals form the deep-scattering layer (DSL).
Cephalopods and dragonfish	Deep-living predatory squids, octopus and fish that are major consumers of myctophids, bristlemouths and krill.
Cetaceans	Multiple species of air-breathing mammals (whales and dolphins) found in the North Atlantic. Pilot whales and the sperm whale (*Physter microcephalus*) can dive to approximately 1000 m and consume large quantities of deep-sea cephalopods.
Deep nekton	Swimming animals that live in the vast volume of dark ocean between 1000 m depth and the abyssal seafloor. Includes rarely seen fishes, squids, octopuses and crustaceans that prey on each other and deep plankton.
Deep pelagic plankton	Planktonic animals that live permanently below 1000 m depth. Includes copepods, medusas, and gelatinous animals that consume particulate organic matter.
Swimming predators	Predators that can actively move above the seafloor to catch their prey. Includes deep-sea sharks (down to 3000 m) grenadier fishes, cephalopods and crustaceans such as amphipods.
Epifauna detritivores	Organisms that feed on detritus that accumulates on the surface of the seafloor. Includes some sea cucumbers, crustaceans, segmented worms and enteropneusts.
Epifauna predators	Predators that feed on prey occurring on the surface of the seafloor. Includes some fishes, crustaceans, bristleworms and cephalopods.
Sessile filter feeders	Organisms that are attached to the seafloor and feed by straining particles or small organisms from the passing water flow. Includes corals, sponges, sea lilies and fanworms.

Mobile infauna predators	Predators that can move and are living within the sediment of the seafloor. Includes some molluscs, crustaceans, segmented worms, bristleworms and nematodes.
Infauna detritivores	Burrowing organisms that feed on detritus that accumulates within the sediment of the seafloor. Includes some sea cucumbers, bristleworms, segmented worms and nematodes.
Benthic microbes	Microorganisms that live in the seafloor (benthic) environment and degrade organic matter. Includes some Bacteria and Archaea.

Below: Figure 1. Images of representative organisms from each of the ecosystem components in the model. a) Turtles: Green turtle (*Chelonia mydas*); b) Surface nekton: pelagic crustacean; c) Fish: Blue fin tuna (*Thunnus thynnus*); d) Birds: Fulmar (*Fulmarus glacialis*), e) Plankton: mixed sample of zooplankton - copepods, salps and larvae; f) Particulate Organic Matter (POM): marine snow particles obscuring view of a deep-sea shark; g) Myctophids, bristlemouths and krill: Myctophid, Spotted lantern fish (*Myctophum punctatum*); h) Cephalopods and dragonfish: cephalopod, deep-sea squid; i) Cetaceans: Sperm whale (*Physeter macrocephalus*); j) Deep nekton: Football fish (*Himatolophus* sp.); k) Deep pelagic plankton: bathypelagic medusa; l) Swimming predators: abyssal grenadier fish (*Coryphaenoids armatus*); m) Epifauna detritivores: abyssal sea cucumber; n) Epifaunal predator: abyssal prawn (*Cerataspis monstrosus*); o) Sessile filter feeders: sea lily; p) Mobile infauna predator: bristle worm (*Eunoe bathydomus*); q) Infauna detritivores: nematode worm; r) Benthic microbes: deep-sea bacteria (green dots) feeding on a particle of detritus (orange) viewed under light microscopy. Image Credits: Bernard Dupont[4] (a); Øystein Paulsen - MAR-ECO[5] (b); aes256[6] (c); David Shale, ECOMAR (d, g, h, j, k, o & p); Adriana Zingone et al. LTER-MC team[7] (e); Alan Jamieson & Thom Linley, University of Newcastle (f, m & n); Gabriel Barathieu[8] (i); Alan Jamieson, Oceanlab, Aberdeen (l); Nikolaos Lampadariuou, HCMR (q); and Roberto Danavaro (r).

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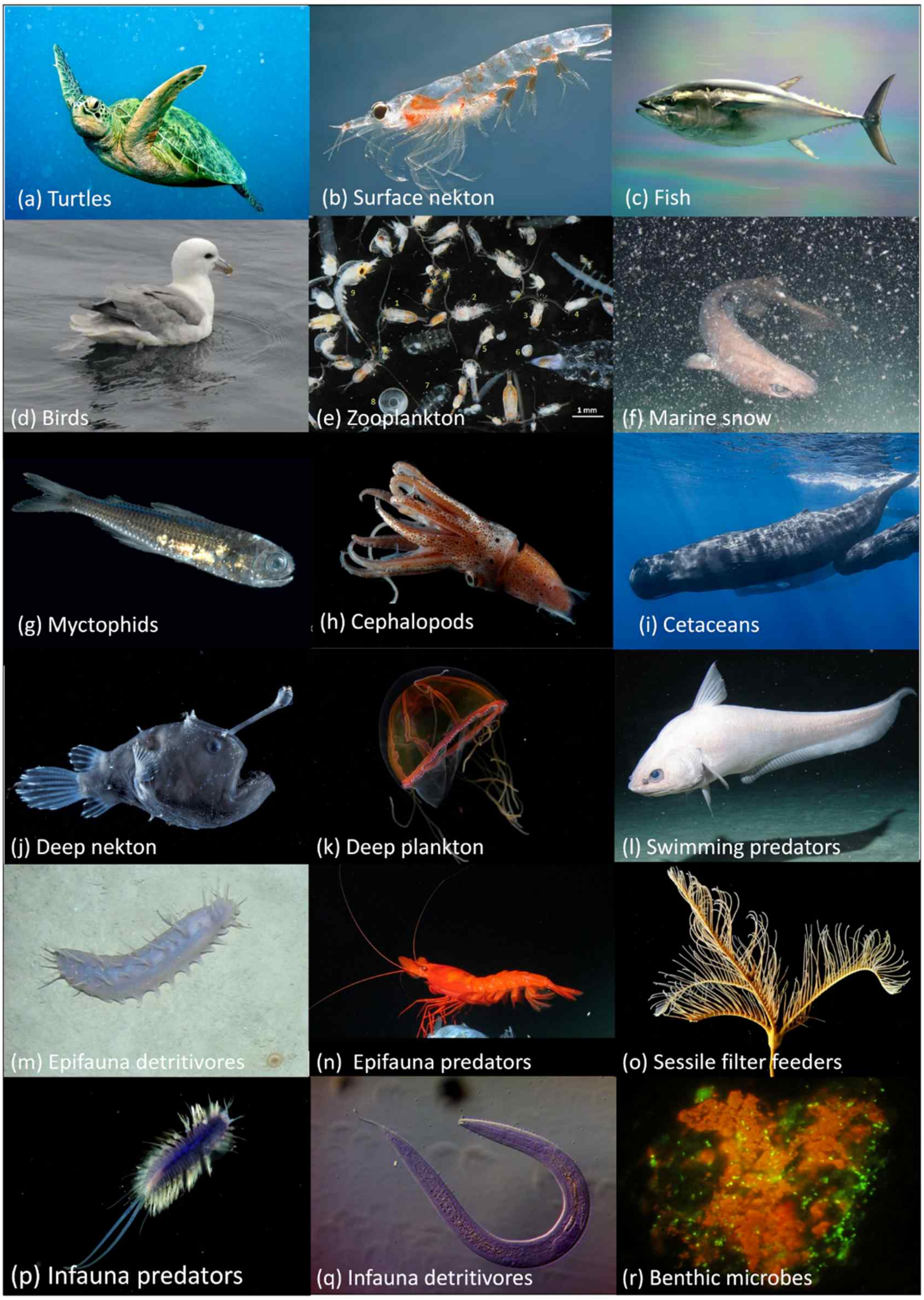
[4] https://commons.wikimedia.org/wiki/File:Green_Turtle_(Chelonia_mydas)_(6133097910).jpg

[5] https://en.wikipedia.org/wiki/Krill#/media/File:Meganyctiphanes_norvegica2.jpg

[6] https://commons.wikimedia.org/wiki/File:Pacific_bluefin_tuna.jpg

[7] https://doi.org/10.3897/natureconservation.34.30789

[8] https://commons.wikimedia.org/wiki/File:Mother_and_baby_sperm_whale.jpg


(a) Turtles
(b) Surface nekton
(c) Fish
(d) Birds
(e) Zooplankton
1 mm
(f) Marine snow
(g) Myctophids
(h) Cephalopods
(i) Cetaceans
(j) Deep nekton
(k) Deep plankton
(l) Swimming predators
(m) Epifauna detritivores
(n) Epifauna predators
(o) Sessile filter feeders
(p) Infauna predators
(q) Infauna detritivores
(r) Benthic microbes

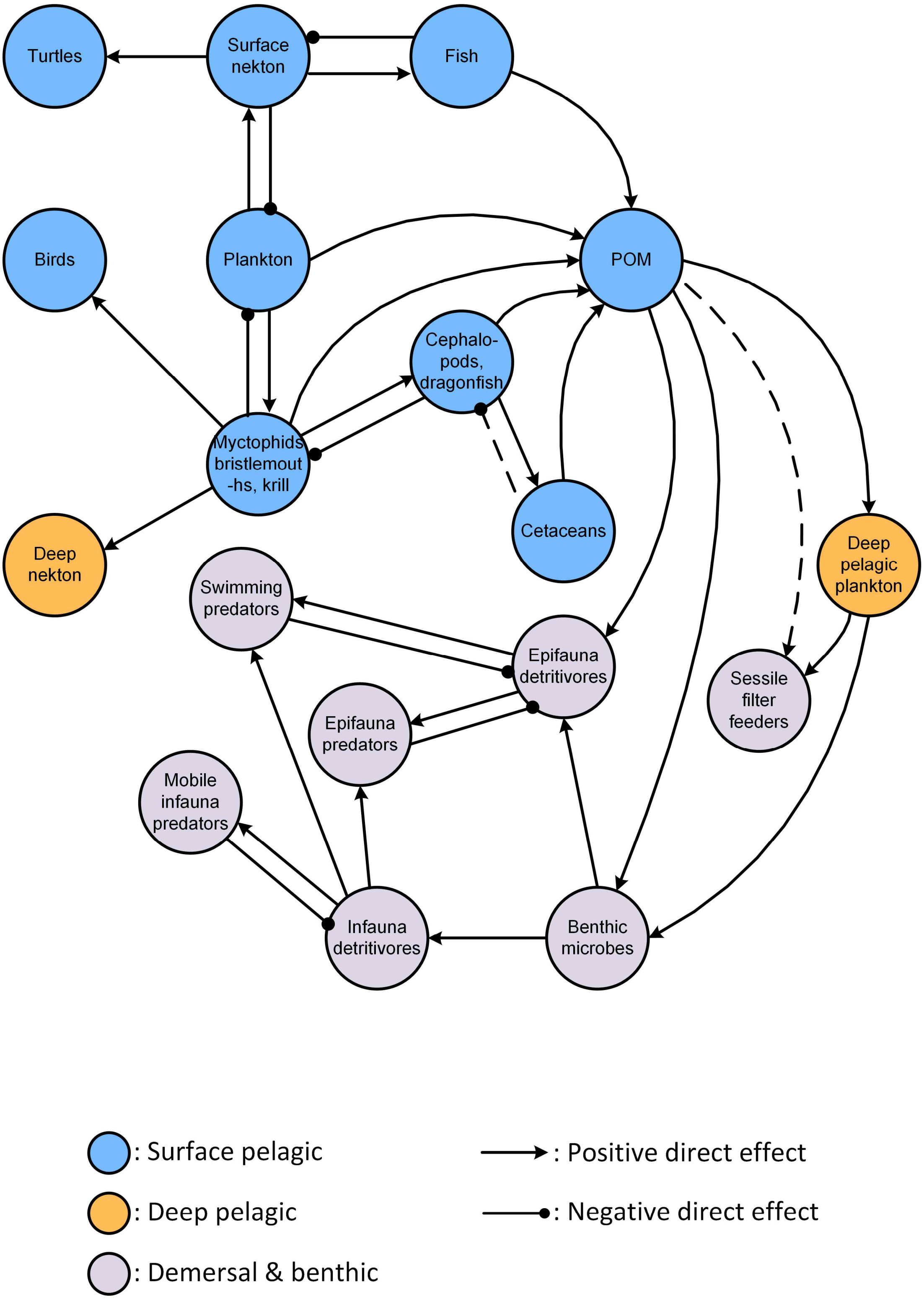


Figure 2. Signed digraph of pelagic and non-hydrothermal sediment habitats of the Mid-Atlantic Ridge constructed from expert elicitation. Model 1 includes all links, while Model 2 omits the two dashed line links.

Table 2. Ecosystem interactions in signed digraph of pelagic and soft sediment habitats of the Mid-Atlantic Ridge (Figure 1); effects are positive (←) or negative (•—) in sign.

Effect to	**Effect sign**	**Effect from**	**Description**	**Reference**
Turtles	←	Surface nekton	Benefit of consumption	Bjorndal (1997), SeeTurtles.org (2020), Witherington (2002)
Surface nekton	•—	Fish	Predation mortality	Morato et al. (2016)
	←	Plankton	Benefit of consumption	Morato et al. (2016)
Fish	←	Surface nekton	Benefit of consumption	Morato et al. (2016)
Birds	←	Myctophids bristlemouths & krill	Benefit of consumption	Conan et al. (2007), Danielsen et al. (2010), Edwards et al. (2013)
Plankton	•—	Surface nekton, myctophids bristlemouths & krill	Predation mortality	Morato et al. (2016)
POM	←	Fish, plankton, Myctophids bristlemouths & krill cephalopods & dragonfish, cetaceans	Contribution to pool of particulate organic matter from carcasses or excretion of waste products	Anderson et al. (2019)
Cephalopods & dragonfish	←	Myctophids bristlemouths & krill	Benefit of consumption	Drazen & Sutton (2016), Morato et al. (2016), Priede (2017), Sutton et al. (1996)
Myctophids bristlemouths & krill	•—	Cephalopods & dragonfish	Predation mortality	Drazen & Sutton (2016), Priede (2017), Sutton et al. (1996)
Cephalopods & dragonfish	•—	Cetaceans	Predation mortality. Relative strength uncertain and could be negligible	Morato et al. (2016)
Myctophids bristlemouths & krill	←	Plankton	Benefit of consumption	Anderson et al. (2019), Drazen & Sutton (2016), Morato et al. (2016), Priede (2017), Sutton et al. (1996)
	•—	Cephalopods & dragonfish	Predation mortality	Anderson et al. (2019) Morato et al. (2016)
Cetaceans	←	Cephalopods & dragonfish	Benefit of consumption	Morato et al. (2016), Sptixz et al. (2011)
Deep nekton	←	Myctophids bristlemouths & krill	Benefit of consumption	Bergtad et al (2010), Morato et al. (2016)
Deep pelagic plankton	←	POM	Benefit of consumption	Anderson et al. (2019), Morato et al. (2016)
Swimming predators	←	Infauna detritivores, epifauna detritivores	Benefit of consumption	Drazen & Sutton (2016)
Epifauna detritivores	←	POM, Benthic microbes	Benefit of consumption	Amaro et al. (2012, 2010, 2009), Billett et al. (2001), Smith et al. (2006)
	•—	Swimming predators, epifauna predators	Predation mortality	Drazen & Sutton (2016)
Epifauna predators	←	Epifauna detritivores, infauna detritivores	Benefit of consumption	Expert Opinion
Sessile filter feeders	←	POM, deep pelagic plankton	Benefit of consumption; relative strength of effect from POM uncertain and could be negligible	Leys et al. (1998, 2006)
Mobile infauna predators	←	Infauna detritivores	Benefit of consumption	Expert Opinion
Infauna detritivores	←	Benthic microbes	Benefit of consumption	Amaro et al. (2012), Danovaro et al. (2008)
	•—	Mobile infauna predators	Predation mortality	Expert Opinion

Effect to	Effect sign	Effect from	Description	Reference
Benthic microbes	←	POM	Precipitation of POM to benthos and consumption by microbes	Expert Opinion
	←	Deep pelagic plankton	Contribution to POM in benthos from carcasses or excretion of waste products and consumption by microbes	Alldredge & Silver (1988)

Pressures on the ecosystem model

Potential pressures to this ecosystem were described for climate change and future mineral exploitation activities (Table 3). These two classes of pressures were kept separate in the perturbation combinations (Table 4) as future exploitation of PMS on the MAR and climate change are anticipated to happen on different timescales. The time period when PMS exploitation may occur on the MAR is unknown but could possibly be within the next decade, perhaps before 2030 (Boschen-Rose et al. 2020). For climate change, it was noted that atmospheric global warming will likely reach 1.5°C between 2030 and 2052 (IPCC, 2018). Global sea surface temperature change is likely to exceed 1.5°C by 2100 in all representative concentration pathway (RCP) scenarios, except the low emission scenario RCP 2.6 (IPCC, 2013). Although ocean warming will not be regionally uniform, it will occur over a considerably larger scale compared to the more localised extent of exploitation activities on a single PMS deposit. On the northern MAR, multiple climate variables are projected to see future variability exceeding historical variability by 2030 under the high emission scenario RCP 8.5, with the time of emergence for all four climate drivers under RCP 8.5 and RCP 2.6 being at the earliest 2031 and 2036 respectively (Levin et al. 2020).

In the future, it will be important to consider cumulative pressures from climate change and PMS exploitation acting concurrently but for the purpose of this exercise, these pressures were assessed separately.

Climate Change

Under the climate change scenarios, both an increase in ocean water temperature and a decrease in pH were initially considered. Decreasing ocean pH was deemed to be important on longer time scales with uncertain effects, such that it was not possible to address in the current modelling exercise. It was deemed possible that significant increases in ocean temperature could occur in the North Atlantic on timescales similar to potential future PMS exploitation, as a result, the pressures associated with higher ocean temperatures were qualitatively assessed in the exercise. An increase in water temperature was depicted as affecting the trophic linkages between phytoplankton and zooplankton populations through an uncertain shift in production from large and small diatoms to bacteria. This shift in production would likely have an impact on the quality of POM as a food resource. According to Nomaki et al. (submitted), this shift can have negative impacts on the benthic deep-sea eukaryotes but positive effects on prokaryotes, significantly reducing the energy transfer to the higher trophic levels of deep-sea benthic ecosystems.

Future polymetallic sulphide exploitation

Exploitation activities for PMS have the potential to impact the pelagic environment (Drazen et al. 2019; Drazen et al. 2020), although there are many unknowns relating to the precise nature and extent of these impacts. Potential impacts from exploitation activities that are relevant to pelagic and non-hydrothermal sediment habitats include the removal of overburden and deposition at the seabed; disaggregation and removal of PMS deposit material from the seafloor and transport to the surface; discharge of return water at the surface, in the midwater or seafloor following shipboard processing; and other activities of the surface support vessels. These mineral exploitation activities were described through thirteen distinct pressures that directly impact multiple components of the pelagic and non-hydrothermal sediment ecosystem (Table 3).

Activities such as removal of overburden and deposition, removal of PMS deposits at the seafloor, and return of water from shipboard processing have the potential to generate plumes with a suspended particle component and a dissolved component, which could include potentially toxic contaminants. Discharge of return water at the surface or near the seafloor could also introduce water with different physical and chemical properties into the surface or benthic environments respectively. For example, the return water could have a different temperature, acidity, or oxygen concentration, depending on the time this water spends at the surface during processing and the processing stages it is subjected to. Detailed surface processing information for return water is not yet available. To reflect this, the only pressures related to return water that could be assessed were increased turbidity from surface or seafloor discharge of return water and increased nutrient concentrations in surface discharge. It was considered that discharge of return water in the surface environment could introduce deep-water enriched with nutrients into the surface layer. However, discharge at or near the seafloor would return this water to the environment where it originated and is less likely to increase localised nutrient concentrations.

Although the model uses ‘plankton’ to represent both phytoplankton and zooplankton, these groups have different functions and may respond differently to pressures, through different mechanisms. For example, any increased nutrient input from return water discharge at the surface could stimulate primary production but would not have a direct impact on the zooplankton, unless they graze on an increased abundance of phytoplankton. The particle load or turbidity of return water discharged at the surface could shade phytoplankton, reducing primary production and food available for zooplankton. Increased particle load could also clog zooplankton feeding apparatus, depending on particle size.

Alteration to seafloor habitat was considered through the sedimentation from overburden removal and dumping, and mining vehicle activity on the seafloor. Most of the available literature on the observed impacts of seafloor habitat alteration is based on the response of shallow-water organisms, with far less known about the response of deep-sea benthic invertebrates to disturbances comparable to PMS exploitation. The direct pressures on benthic microbes from exploitation activities are generally unknown.

Mining vehicle activities at the seabed would introduce light and noise into the seafloor environment, whilst pumps within the riser pipe and return water pipe would introduce noise into the water column. The more mobile ecosystem components (e.g. fish and cephalopods) may be able to physically escape the noise from pumping operations, exhibiting a localised escape response. Depending on the depth at which pumps are positioned, these may overlap with the location of the Sound Fixing And Ranging Channel (SoFAR Channel), which could enable any noise generated to propagate for thousands of kilometres with the potential to disrupt cetacean communications at very large spatial scales.

Light and noise would also be produced at the surface from support vessels and pumping operations, which may attract some ecosystem components and cause negative effects. For example, increased light could attract seabirds resulting in increased seabird mortality through direct interaction, such as striking the ship, or indirect interaction through wasting energy reserves by circling the ship, increased susceptibility to predation or interrupting transoceanic migration (Montevecchi 2006). For some ecosystem components, such as turtles, there was no evidence of negative impacts from artificial light emitted by structures and vessels at sea (Lohmann, 1992; Lohmann & Lohmann, 1993; Lohmann & Lohmann, 1996; Mathger et al 2011).

Polymetallic sulphide exploitation scenarios

Two PMS exploitation scenarios were considered for simplicity and to test the applicability of the approach. Each scenario involved the removal of sediment overburden; disaggregation of PMS on the seafloor and pumping to the surface; dewatering at the surface; and discharge of the return water from surface processing. The two scenarios differed in where the return water was discharged, to reflect the two extremes of potential return water discharge scenarios. It is also possible that return water may be discharged in the midwater environment, however there was insufficient information available on the probable return depth to assess this as a scenario.

- **Scenario 1**: Return water from surface dewatering is discharged in the surface environment (surface – 200 m water depth)

- **Scenario 2**: Return water from surface dewatering is discharged in the benthic environment (seafloor – 50 m above seafloor) or within the lower midwater environment, as close to the benthic environment as possible

These exploitation scenarios did not apply strict temporal and spatial boundaries, as the precise spatiotemporal scales of potential impacts from exploitation remain unknown. For the temporal scale, only perturbations that would lead to a long-term shift in ecosystem state were considered. Perturbations that would lead to short term 'pulse' changes, such as increased availability of prey for predators and scavengers following prey injury or mortality as a result of exploitation activities were not considered. Perturbations included in the model were considered to have the potential for multi-year or decadal effects. For the spatial scale, perturbations were assessed in the immediate environment of their effects (pseudo site-scale) and not across the region as a whole. Greater certainty on the spatiotemporal scales of potential impacts from PMS exploitation would enable more precise spatial and temporal boundaries to be applied in future modelling exercises.

Table 3. Potential pressures from climate change and future polymetallic sulphide exploitation on pelagic and non-hydrothermal sediment habitats of the Mid-Atlantic Ridge. Inv: inverted sign of perturbation effect.

Pressure	**Perturbation effect number and sign**	**Direct effect on**	**Description**	**Reference**
Increased temperature	P1) positive or P1inv) negative	POM	Change in carbon balance of POM, and hence its quality as food resource, due to shift in production from small and large diatoms to bacteria. Positive effect on prokaryotes and negative on benthic eukaryotes.	Nomaki et al. (submitted)
	P2) positive or P2inv) negative	Plankton	Change in primary production (phytoplankton) may impact secondary production (zooplankton). Uncertain if effect will be positive or negative.	Nagelkerken & Connell (2015), Nohe et al. (2020)
Light from exploitation activities at depth	P3) positive or P3inv) negative	Cetaceans, swimming predators	Potential impact on foraging efficiency due to avoidance or attraction of large predators from lighted areas and either avoidance or attraction of prey to the light. Damage to eyes.	Kochevar (1998)
Light from tender vessels at surface	P4) positive	Fish, turtles	Increased availability of prey attracted to light.	Peña (2019), Røstad, et al. (2006)
	P4) negative	Seabirds	Attraction to lit installations causes individual injury and mortality from colliding with the vessel and infrastructure.	Montevecchi (2006)
	P4) negative	Nekton	Attraction to lighted areas increases predation mortality.	Røstad, et al. (2006)
	P4) negative	Myctophids bristlemouths & krill	Detrimental change in behaviour due to avoidance of light; uncertain effect.	Allen et al (2018), Clark et al. (2009), Croll et al. (2001), Donovan et al. (2017), Ellison et al. (2012), Findlay et al. (2018), Greene (1987), Harris et al. (2017), Haver et al. (2017), Hawkins et al. (2018), Hilderbrand, (2009), Mooney et al. (2012), Nabi et al. (2018), Parks et al. (2014), Parsons et al. (2009), Peña (2019), Pirotta et al. (2012,

Pressure	Perturbation effect number and sign	Direct effect on	Description	Reference
				2019), Roland et al. (2012), Smith et al. (2004), Weilgart (2007), Wilcock et al. (2014)
Noise of exploitation activities at depth	P5) negative	Cetaceans	Detrimental change in behaviour.	Erbe et al. (2018)
Noise of tender vessels at surface	P6) negative	Turtles, cetaceans	Detrimental change in behaviour.	Rolland et al. (2012), Simmons et al. (2018)
Noise from pumping activities using vertical pipes	P7) negative	Plankton, myctophids bristlemouths & krill, cephalopods and dragonfish, cetaceans, deep nekton	Detrimental change in behaviour.	Andre et al. (2011), Kaartvedt et al. (2020), Packard et al. (1990), Peña (2019), Røstad, et al. (2006), Sole et al. (2013)
Sedimentation from overburden removal and dumping and mining vehicle activity on the seafloor	P8) negative	Benthic microbes, sessile filter feeders, epifauna detritivores, infauna detritivores, infauna predators	Burial and smothering of individuals and their food source.	Bock & Miller (1996), Boyd et al. (2005), Ellis et al. (2002), Thrush & Dayton (2002), Tompkins-MacDonald & Leys (2008), Vonnahme et al. (2020)
High turbidity return water discharged at the surface	P9) negative	Plankton	Turbidity reduction of primary production.	Chan & Anderson (1981), Diehl (2002)
	P9) negative	Surface nekton, fish	Turbidity interference with respiration through irritation or clogging of gills.	Wilber & Clarke (2001)
High turbidity return water discharged at or near the seabed	P10) negative	Deep pelagic plankton, sessile filter feeders, epifauna detritivores, infauna detritivores, infauna predators, swimming predators	Turbidity suppression of consumption of POM through clogging of feeding apparatus, smothering, and burial of food source.	Drazen et al. (2020), Ellis et al. (2002)
Increased toxicants from sediment resuspension at the seafloor	P11) negative	Benthic microbes, sessile filter feeders, epifauna detritivores, infauna detritivores, infauna predators, swimming predators	Loss of reproductive capacity or increased mortality. Some swimming predators may be able to avoid impacted areas.	Knott et al. (2018), Mestre et al. (2017), Roberts (2012)
Increased nutrients in return water discharged at the surface	P12) positive	Plankton	Increased primary production through availability of limiting nutrients.	Bharati et al. (2005), Christiansen et al. (2019), Hernández-Hernández et al. (2018)
Increased nutrients from sediment resuspension at the seafloor	P13) positive	Benthic microbes	Increased secondary production through availability of nutrients from seafloor sediment resuspension resulting from exploitation activity. Increased nutrients could possibly be augmented by any additional nutrients originating from sediment that is included in the return water, where this is returned at or near the seafloor. If return water includes water originating from the surface, this could reduce the concentration of nutrients in return water being returned to the seafloor.	Boliger et al. (1991)

Perturbation combinations for pressures modelling

The thirteen possible pressure effects, emanating from the PMS exploitation activities and climate change pressures detailed in Table 3, were combined into eight separate perturbation scenarios (Table 4). A very large number of pressure effect combinations (> 8,000) was possible in this exercise. The perturbation scenarios presented in Table 4 were selected to reflect a parsimonious combination of pressure effects that could be presented in a set of potential perturbation scenarios to demonstrate the approach.

Table 4. Perturbation scenarios assembled from combined effects of pressures (Table 3) from climate change or future polymetallic sulphide exploitation on pelagic and non-hydrothermal sediment habitats of the Mid-Atlantic Ridge.

Perturbation scenario	**Perturbation effect number from Table 3**	**Brief perturbation description**
S1a	P3, P4–P9, P11–P13	Return water is discharged at the surface. There is a positive effect on cetaceans and swimming predators from light.
S1b	P3inv, P4–P9, P11–P13	Return water is discharged at the surface. There is a negative effect on cetaceans and swimming predators from light.
S2a	P3, P4–P8, P10, P11, P13	Return water is discharged at or near the seabed. There is a positive effect on cetaceans and swimming predators from light.
S2b	P3inv, P4–P8, P10, P11, P13	Return water is discharged at or near the seabed. There is a positive effect on cetaceans and swimming predators from light.
CC1	P1, P2	Increased ocean temperature due to climate change has a positive effect on the quality of POM and the primary productivity of plankton.
CC2	P1inv, P2inv	Increased ocean temperature due to climate change has a negative effect on the quality of POM and the primary productivity of plankton.
CC3	P1, P2inv	Increased ocean temperature due to climate change has a positive effect on the quality of POM and a negative effect on the primary productivity of plankton.
CC4	P1inv, P2	Increased ocean temperature due to climate change has a negative effect on the quality of POM and a positive effect on the primary productivity of plankton.

For PMS exploitation Scenario 1, where the return water is discharged at the surface, both perturbation scenarios (S1a and S1b, Table 4) include the following pressures: light from tender vessels at night (P4); noise of exploitation activities at depth (P5); noise of tender vessels at surface (P6); noise from pumping activities using vertical pipes (P7); sedimentation from overburden removal and dumping and mining vehicle activity on the seafloor (P8); high turbidity return water discharged at the surface (P9); increased toxicants from sediment resuspension at the seafloor (P11); increased nutrients in return water discharged at the surface (P12), and increased nutrients from sediment resuspension at the seafloor (P13). The only difference between the two perturbation scenarios is that there is a positive effect of light from exploitation activities at depth (P3) on cetaceans and swimming predators in S1a, and a negative effect of this pressure (P3inv) on the same components in S1b.

In PMS exploitation Scenario 2, where the return water is discharged at or near the seafloor, both perturbation scenarios (S2a and S2b, Table 4) include the following pressures: light from tender vessels at night (P4); noise of exploitation activities at depth (P5); noise of tender vessels at surface (P6); noise from pumping activities using vertical pipes (P7); sedimentation from overburden removal and dumping and mining vehicle activity on the seafloor (P8); high turbidity return water discharged at or near the seabed (P10); increased toxicants from sediment resuspension at the seafloor (P11); and increased nutrients from sediment resuspension at the seafloor (P13). The only difference between the two perturbation scenarios is that there is a positive effect of light from exploitation activities at depth (P3) on cetaceans and swimming predators in S2a, and a negative effect of this pressure (P3inv) on the same components in S2b.

Within the climate change perturbation scenarios (CC1 – CC4, Table 4), each scenario has a different combination of effects relating to increased temperature. For CC1, increased temperature had a positive effect on the carbon balance of POM, enhancing its quality as a food resource (P1) and a positive effect on primary production of phytoplankton (P2). In CC2, increased temperature had negative effects on both POM (P1inv) and plankton (P2inv). Within CC3, increased temperature had a positive effect on

POM (P1) but a negative effect on plankton (P2inv). Finally, in CC4, increased temperature had a negative effect on quality of POM (P1inv) but a positive effect on the primary production of plankton (P2).

Outcomes from the qualitative modelling exercise

The predicted responses of ecosystem components in the model to individual or multiple pressures were classified according to their probability for sign determinacy as either certain negative, likely negative, zero, likely positive, certain positive, or sign indeterminate. Certain positive or negative responses were predicted where all pathways of linkages leading from a pressure to an ecosystem component were of the same sign and the probability for sign determinacy is 100%. Zero responses were predicted where the ecosystem component had an absence of any effects being transmitted from the pressure. Likely positive or negative responses were predicted where the majority of pathways caused effects with the same sign and the probability for sign determinacy is ≥80%.

Cumulative impact single pressures

The sixteen individual pressures detailed in Table 3 were used to predict the cumulative impact on the eighteen ecosystem components through the web of interactions provided in the ecosystem model. The responses of ecosystem components to individual pressures in Model 1 and Model 2 are broadly similar, although there are subtle differences between the two models. In Model 1 (Figure 3), the benefits of POM consumption by sessile filter feeders and the control of cephalopod and dragon fish populations by cetaceans in included, whereas these links are excluded in Model 2 (Figure 4).

The vast majority of individual exploitation pressures elicited certain negative, likely negative, sign indeterminate (uncertain) or zero (no response) response predictions in ecosystem components, for both Model 1 and 2. Predicted ecosystem component responses to climate change pressures depended on the nature of the pressure.

Polymetallic sulphide exploitation pressures

Exploitation pressures: Outcomes for Model 1

In Model 1 (Figure 3), the PMS exploitation pressure predicted to have the greatest number of negative responses across all ecosystem components was the release of high turbidity return water at the surface (P9), followed by water column noise (P7). All ecosystem components were predicted to have either a certain negative (9 out of 18) or a likely negative response (9 out of 18) to the release of turbid water at the surface. For noise in the water column from pumping activities, the majority of ecosystem components were predicted to have a certain negative response (10 out of 18), followed by likely negative (4 out of 18) and sign indeterminate responses (4 out of 18).

For the other PMS exploitation pressures, some were predicted to have a combination of negative, sign indeterminate (uncertain) and zero (no response) responses, some were predicted to have mixed responses including positive and negative responses, and two exploitation pressures had predominantly positive responses. The exploitation pressures predicted to have a combination of negative, sign indeterminate and zero responses were release of turbid return water at the seafloor (P10), resuspension of toxicants at the seafloor (P11), and seafloor sedimentation from overburden removal and dumping and mining vehicle activity (P8). For each of these pressures it was predicted that there would be a large proportion of zero responses (10 or 11 out of 18) corresponding to the majority of ecosystem components in the surface pelagic and deep pelagic environment (birds, turtles, cetaceans, plankton, POM, surface nekton, fish, myctophids bristlemouths and krill, cephalopods and dragon fish, deep nekton). Deep pelagic plankton were predicted to have a zero response to seafloor sedimentation and toxicant release but a certain negative response to turbid water discharged at the seafloor. Within the demersal and benthic ecosystem components, benthic microbes, sessile filter feeders and mobile infauna predators were predicted to have certain negative responses to seafloor sedimentation, toxicant release and turbid water discharged at the seafloor. Infauna detritivores and epifauna predators were predicted to have likely negative responses to the same pressures. Swimming predators were predicted to have certain negative responses to turbid water discharged at the seafloor and seafloor toxicants but a likely negative response to seafloor sedimentation. Epifauna detritivores were predicted to have sign indeterminate responses to turbid water discharge at the seafloor and toxicant release, but a likely negative response to seafloor sedimentation.

The exploitation pressures that were predicted to have mixed responses included light from tender vessels at the surface (P4), surface noise (P6), seafloor light where there was a positive (P3) or negative (P3inv) effect on predation by cetaceans and swimming predators, and seafloor noise (P5). For each of these pressures it was predicted that there would be a high degree of uncertainty in ecosystem component response, reflected in the large numbers of sign indeterminate responses (5 to 7 out of 18) compared to other pressures. The ecosystem components that were most often predicted to have sign indeterminate responses were POM, deep pelagic plankton, epifauna detritivores, infauna detritivores, epifauna predators, mobile infauna predators, and swimming predators.

The only two exploitation pressures that were predicted to elicit only positive, zero or sign indeterminate responses were increased nutrients from return water discharged at the surface (P12) and increased nutrients from sediment resuspension at the seafloor (P13). For increased nutrients in the surface, all ecosystem components were predicted to have a certain positive response, apart from epifauna detritivores, which was predicted to have a likely positive response. For increased nutrients at the seafloor, benthic microbes, infauna detritivores and mobile infauna predators were predicted to have a certain positive response, epifauna predators and swimming predators were predicted to have a likely certain positive response, and epifauna detritivores were predicted to have a sign indeterminate response. For all other ecosystem components (12 out of 18), it was predicted that increased nutrients at the seafloor would elicit a zero response, which largely resulted from all of these components being restricted to the surface pelagic or deep pelagic environment, apart from sessile filter feeders.

Exploitation pressures: Outcomes for Model 2

The results for Model 2 (Figure 4) were broadly comparable to Model 1. The two exploitation pressures that were predicted to have the greatest number of negative responses across all ecosystem components were the release of high turbidity return water at the surface (P9) and water column noise (P7). The same ecosystem components as in Model 1 were predicted to have a certain negative (9 out of 18) or likely negative (7 out of 18) response to the release of turbid water at the surface, apart from surface nekton and turtles, which were predicted to have a sign indeterminate (uncertain) response in Model 2, compared to a likely negative response in Model 1. The predicted response of ecosystem components to water column noise was subtly different in Model 2 compared to Model 1. The majority of predicted certain negative responses in Model 2 (10 out of 18) were replicated in Model 1, apart from cephalopods and dragonfish, which were predicted to have a certain negative response to water column noise in Model 2 and a likely negative response in Model 1. Conversely, deep nekton were predicted to have a likely negative response to water column noise in Model 2 and a certain negative response in Model 1. It was predicted that there would be a greater number of likely negative responses to water column noise in Model 2 (6 out of 18) compared to Model 1 (4 out of 18), with six ecosystem components switching between likely negative and sign indeterminate responses between the models. Birds, and myctophids bristlemouths and krill, were predicted to have sign indeterminate responses to water column noise in Model 2 compared to Model 1, whereas turtles, plankton, surface nekton, fish, were predicted to have likely negative responses in Model 2 compared to sign indeterminate responses in Model 1.

As in Model 1, for the other exploitation pressures, some pressures resulted in a combination of predicted negative, sign indeterminate and zero responses across ecosystem components, one pressure elicited mixed responses including predicted positive and negative responses, and some pressures were predicted to elicit predominantly positive responses. The differences between the outcomes of the two models relate to the identity of the pressures that are predicted to elicit these three broad response types. There was a greater number of exploitation pressures predicted to elicit a combination of negative, sign indeterminate and zero responses in Model 2 compared to Model 1. As for Model 1, in Model 2 pressures predicted to elicit negative, sign indeterminate and zero responses included the release of turbid return water at the seafloor (P10), resuspension of toxicants at the seafloor (P11), and seafloor sedimentation from overburden removal and dumping and mining vehicle activity (P8). In addition to these pressures, in Model 2 a combination of negative, sign indeterminate and zero responses were also predicted from surface noise (P6), the negative effect of seafloor light on predation by cetaceans and swimming predators (P3inv), and seafloor noise (P5). For the pressures that were predicted to elicit a combination of negative, sign indeterminate and zero responses for both models, there was less uncertainty in predicted responses in Model 2, with fewer sign indeterminate responses (1 out of 18) compared to Model 1 (6 or 7 out of 18). Epifauna detritivores exhibited the greatest uncertainty in predicted response to individual pressures in Model 2, with a larger number of sign indeterminate responses in Model 2 (11 out of 18) than in Model 1 (8 out of 18). For all of the six pressures predicted to elicit a combination of negative, sign indeterminate and zero responses for Model 2, there was a large number of predicted zero responses. In Model 1 and 2 there was the same number of ecosystem components with predicted zero responses (10 or 11 out of 18) to the release of turbid return water at the seafloor, resuspension of toxicants at the seafloor, and seafloor sedimentation from overburden removal and dumping and mining vehicle activity. As in Model 1, these predicted zero response in Model 2 largely corresponded to ecosystem components in the surface pelagic and deep pelagic environments. In Model 2, there was also a large number of ecosystem components predicted to have a zero response (7 or 8 out of 18) to surface noise, the negative effect of seafloor light on predation by cetaceans and swimming predators, and seafloor noise; again, these zero response largely corresponded to ecosystem components in the surface pelagic and deep pelagic environments.

The only exploitation pressure in Model 2 where ecosystem components were predicted to have a mixed response was light from tender vessels at the surface (P4). Ecosystem components in Model 2 were predicted to have the same response to surface light as in Model 1, except for birds, which were predicted to have a likely negative response in Model 2 and a certain positive response in Model 1; turtles, which were predicted to have a sign indeterminate response in Model 2 and a likely positive response in Model 1; and benthic microbes and sessile filter feeders, which were predicted to have a likely positive response in Model 2 and a certain positive response in Model 1.

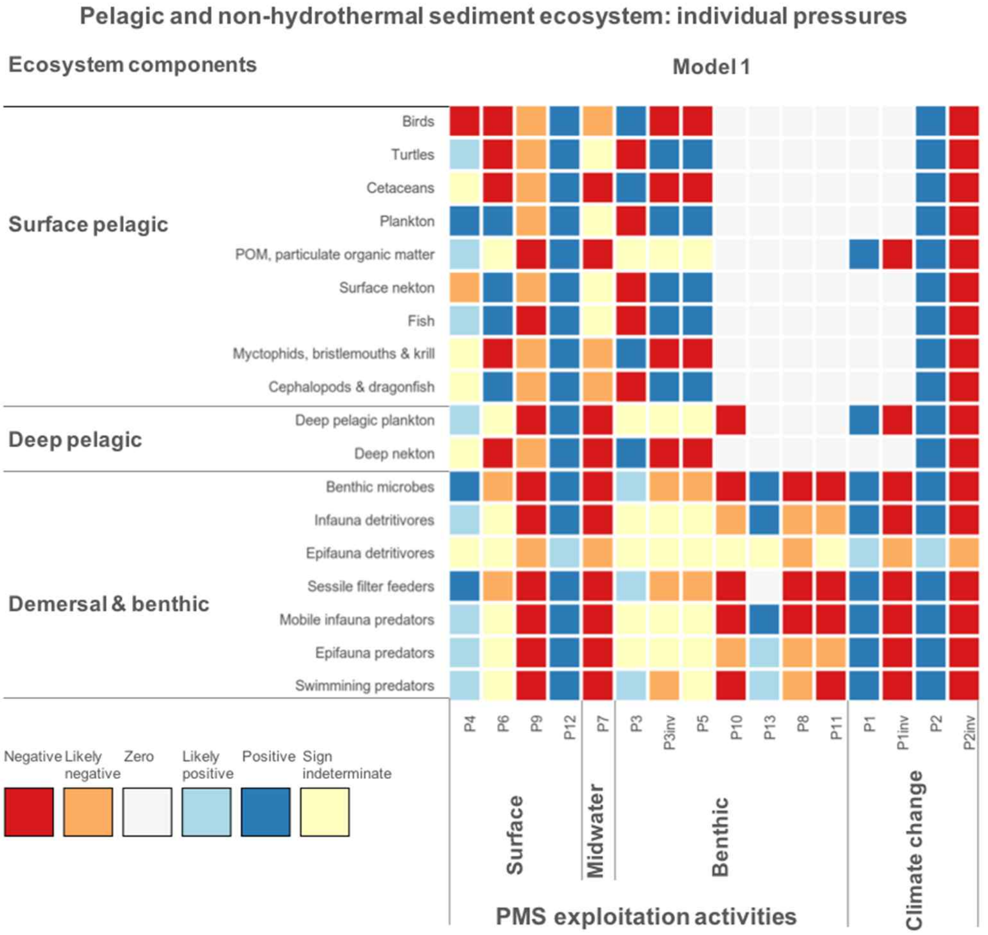
In Model 2, there were three PMS exploitation pressures predicted to elicit a combination of positive, zero or sign indeterminate responses across ecosystem components, compared to two PMS exploitation pressures predicted to elicit these responses for Model 1. As for Model 1, in Model 2 pressures predicted to elicit positive, zero or sign indeterminate responses included increased nutrients from return water discharged at the surface (P12) and increased nutrients from sediment resuspension at the seafloor (P13). In addition to these pressures, in Model 2 the positive effect of seafloor light on predation by cetaceans and swimming predators (P3) was also predicted to elicit positive, zero or sign indeterminate responses. For the two nutrient-related pressures, ecosystem components had the same predicted response in Model 2 as in Model 1. For the positive effect of seafloor light on predation by cetaceans and swimming predators, there were multiple differences in the predicted ecosystem component responses to this in Model 2 compared to Model 1. There were no predicted certain negative responses to this pressure in Model 2; all of the predicted certain negative responses in Model 1 were zero responses in Model 2. There was a larger number of predicted certain positive responses to the positive effect of seafloor light in Model 2 (8 out of 18) compared to Model 1 (4 out of 18). There were also fewer predicted sign indeterminate responses (less uncertainty) to the positive effect of seafloor light in Model 2 (1 out of 18) compared to Model 1 (6 out of 18).

Climate change pressures

Climate change pressures: Outcomes for Model 1 and Model 2

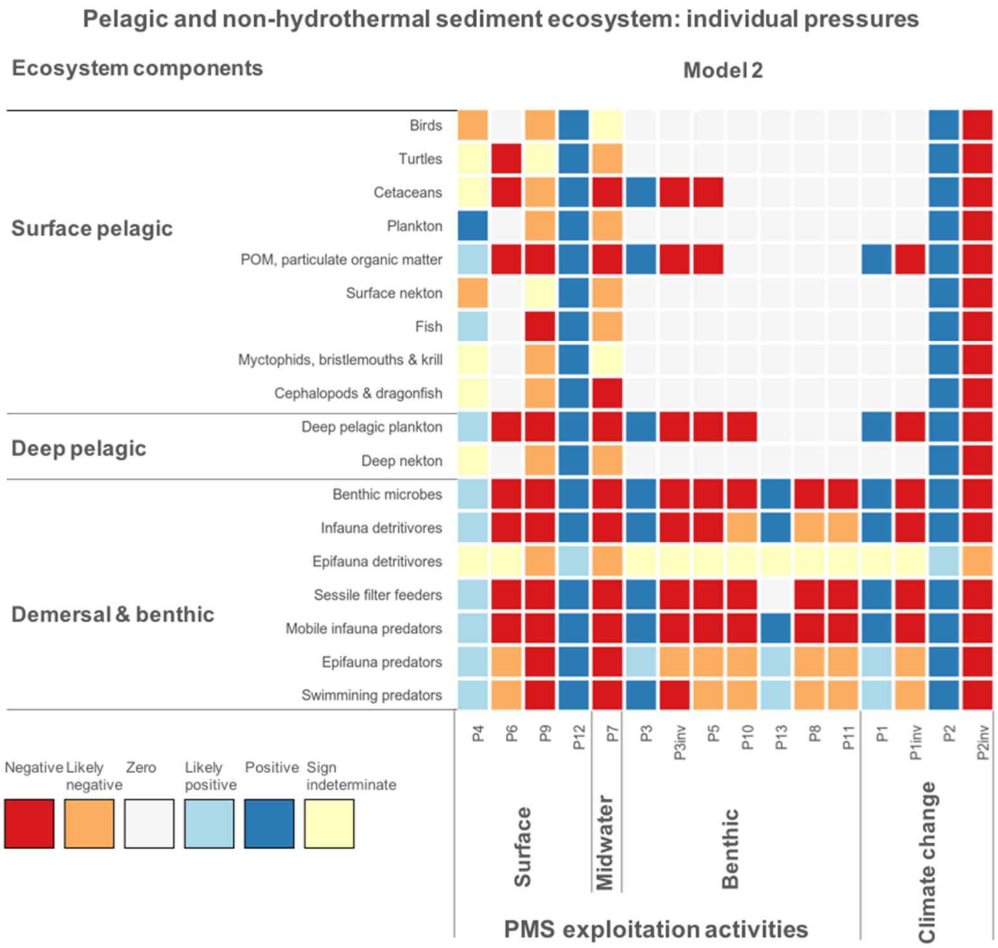
In both Model 1 (Figure 3) and Model 2 (Figure 4), the climate change pressure that was predicted to be more negative overall for the greatest number of ecosystem components was where increased ocean temperature led to a negative effect on the primary production of plankton (P2inv). For this pressure, all ecosystem components were predicted to have a certain negative response, apart from epifauna detritivores which were predicted to have a likely negative response. In both Model 1 and 2, the climate change pressure that was predicted to be the most positive overall for the greatest number of ecosystem components was where increased ocean temperature led to a positive effect on the primary production of plankton (P2). All ecosystem components were predicted to have a certain positive response to this pressure, apart from epifauna detritivores which were predicted to have a likely positive response.

The only differences between Model 1 and Model 2 result from some of the ecosystem components having slightly different predicted responses to the pressures where increased ocean temperature had either a positive effect on POM quality (P1) or a negative effect on POM quality (P1inv). In Model 1, epifauna detritivores were predicted to have a likely positive response to a positive effect on POM, and a likely negative response to a negative effect on POM, whereas in Model 2 this group was predicted to have a sign indeterminate (uncertain) response to both pressures. Epifauna predators and swimming predators were predicted to have a certain positive response to a positive effect on POM and a certain negative response to a negative effect on POM in Model 1, compared to a likely positive or negative response respectively to the same pressures in Model 2. All other ecosystem components had the same response in both Model 1 and 2, with POM, deep pelagic plankton, benthic microbes, infauna detritivores, sessile filter feeders and mobile infauna predators all predicted to have certain positive responses to positive effects on POM, and certain negative responses to negative effects on POM. The vast majority of the surface pelagic and deep pelagic ecosystem components (birds, turtles, cetaceans, plankton, surface nekton, fish, myctophids bristlemouths and krill, cephalopods and dragonfish, deep nekton), except POM and deep pelagic plankton, were all predicted to have zero response (no response) to both pressures related to changes in POM quality.



Pressure category	Abbreviation	Pressure description
Surface	P4	Surface light
	P6	Surface noise
	P9	Turbid water, surface discharge
	P12	Nutrients, surface discharge
Midwater	P7	Water column noise
Benthic	P3	Seafloor light, positive effect
	P3inv	Seafloor light, negative effect
	P5	Seafloor noise
	P10	Turbid water, seafloor discharge
	P13	Nutrients, seafloor resuspension
	P8	Seafloor sedimentation
	P11	Seafloor toxicants
Climate change	P1	Temperature increase, increased POM quality
	P1inv	Temperature increase, reduced POM quality
	P2	Temperature increase, increased primary production
	P2inv	Temperature increase, reduced primary production

Figure 3. Qualitative response predictions of pelagic and non-hydrothermal sediment ecosystem components (rows) in Model 1 to each of the pressure effects (columns) detailed in Table 3. See Figure 2 for the signed digraph of Model 1.



Pressure category	Abbreviation	Pressure description
Surface	P4	Surface light
	P6	Surface noise
	P9	Turbid water, surface discharge
	P12	Nutrients, surface discharge
Midwater	P7	Water column noise
Benthic	P3	Seafloor light, positive effect
	P3inv	Seafloor light, negative effect
	P5	Seafloor noise
	P10	Turbid water, seafloor discharge
	P13	Nutrients, seafloor resuspension
	P8	Seafloor sedimentation
	P11	Seafloor toxicants
Climate change	P1	Temperature increase, increased POM quality
	P1inv	Temperature increase, reduced POM quality
	P2	Temperature increase, increased primary production
	P2inv	Temperature increase, reduced primary production

Figure 4. Qualitative response predictions of pelagic and non-hydrothermal sediment ecosystem components (rows) of Model 2 to each of the pressure effects (columns) detailed in Table 3. See Figure 2 for the signed digraph of Model 2.

Cumulative impact multiple pressures

The eight perturbation scenarios detailed in Table 4 were used to predict the cumulative impact from the various possible pressures resulting from multiple exploitation activities or climate change effects on the pelagic and non-hydrothermal sediment ecosystem (Figure 5).

Polymetallic sulphide exploitation scenarios

A large proportion of the ecosystem components were predicted to have a certain negative response to all four PMS exploitation scenarios. For Model 1, which included the benefits of POM consumption by sessile filter feeders and the control of cephalopod and dragon fish populations by cetaceans, more ecosystem components were predicted to have certain negative responses across all four exploitation scenarios (11 out of 18) compared to in Model 2, where these linkages were omitted (9 out of 18).

Exploitation Scenarios: Outcomes for Model 1

In Model 1 (Figure 5), all PMS exploitation scenarios had a total of 12 ecosystem components predicted to have certain negative responses. There were no certain positive responses predicted in any of the exploitation scenarios. The two PMS exploitation scenarios where return water was discharged at the surface (Scenarios 1a and 1b) were predicted to be more negative overall for a greater number of ecosystem components compared to the two exploitation scenarios where return water was discharged at or near the seafloor (Scenarios 2a and 2b). Scenario 1a, where there was a positive effect on cetaceans and swimming predators from light at the surface, had the greatest number of negative response predictions with the fewest sign indeterminate (uncertain: 1 out of 18) or likely positive (1 out of 18) response predictions. Scenario 1a was closely followed by Scenario 1b, where there was a negative effect on cetaceans and swimming predators from light at the surface. Scenario 1b was predicted to have the second fewest sign indeterminate (0 out of 18) or likely positive responses (2 out of 18). Both Scenarios 1a and 1b were each predicted to have an equal number of likely negative responses (4 out of 18).

Scenario 2a, where there was a positive effect on cetaceans and swimming predators from light at the surface, was more negative than Scenario 2b, where there was a positive effect on cetaceans and swimming predators from light at the surface. There were fewer predicted likely positive responses for Scenario 2a (2 out of 18) than Scenario 2b (3 out of 18) and sign indeterminate responses were only predicted for Scenario 2a (1 out of 18). Both Scenario 2a and 2b were each predicted to have an equal number of likely negative responses (3 out of 18).

In Model 1, most of the same ecosystem components were predicted to have certain negative responses to all exploitation scenarios apart from epifauna detritivores, and myctophids, bristlemouths and krill. Epifauna detritivores were predicted to have a likely negative response in all PMS exploitation scenarios apart from in Scenario 1a, where they were predicted to have a certain negative response where return water was discharged at the surface and there was a positive effect on cetaceans and swimming predators from light at the surface. Myctophids, bristlemouths and krill were predicted to have a certain negative response in all PMS exploitation scenarios apart from in Scenario 1a. Only surface nekton and turtles were predicted to have likely negative responses in all PMS exploitation scenarios. Fish were predicted to have likely negative responses to Scenarios 1a and 1b, where there was discharge of the return water at the surface, and likely positive responses to Scenarios 2a and 2b where the return water was discharged at the seafloor. Cephalopods and dragonfishes were predicted to have a likely positive response to Scenarios 1b and 2b where there was a negative effect on cetaceans and swimming predators from light at the surface, and a sign indeterminate response to Scenarios 1a and 2a where there was a positive effect on cetaceans and swimming predators from light at the surface.

Exploitation Scenarios: Outcomes for Model 2

In Model 2 (Figure 5), all PMS exploitation scenarios were predicted to have a total of 10 ecosystem components with certain negative responses. Overall, each of the four PMS exploitation scenarios were equally negative in terms of the number of ecosystems components with predicted negative responses. For each PMS exploitation scenario, there was an equal number of predicted likely negative (6 out of

18) and sign indeterminate (2 out of 18) responses. There were no certain or likely positive responses predicted in any of the exploitation scenarios.

The only differences between the exploitation scenarios resulted from the distribution of predicted responses amongst ecosystem components. Most of the same ecosystem components were predicted to have certain negative responses to all exploitation scenarios, except cephalopods and dragonfish and epifauna detritivores. Cephalopods and dragonfish were predicted to have a certain negative response to Scenarios 2a and 2b, where discharge of return water was at or near the seafloor, and a likely negative response to Scenarios 1a and 1b where return water discharge was at the surface. Epifauna detritivores were predicted to have a certain negative response to Scenarios 1a and 1b where return water discharge was at the surface, and a likely negative response to Scenarios 2a and 2b where return water discharge was at or near the seafloor.

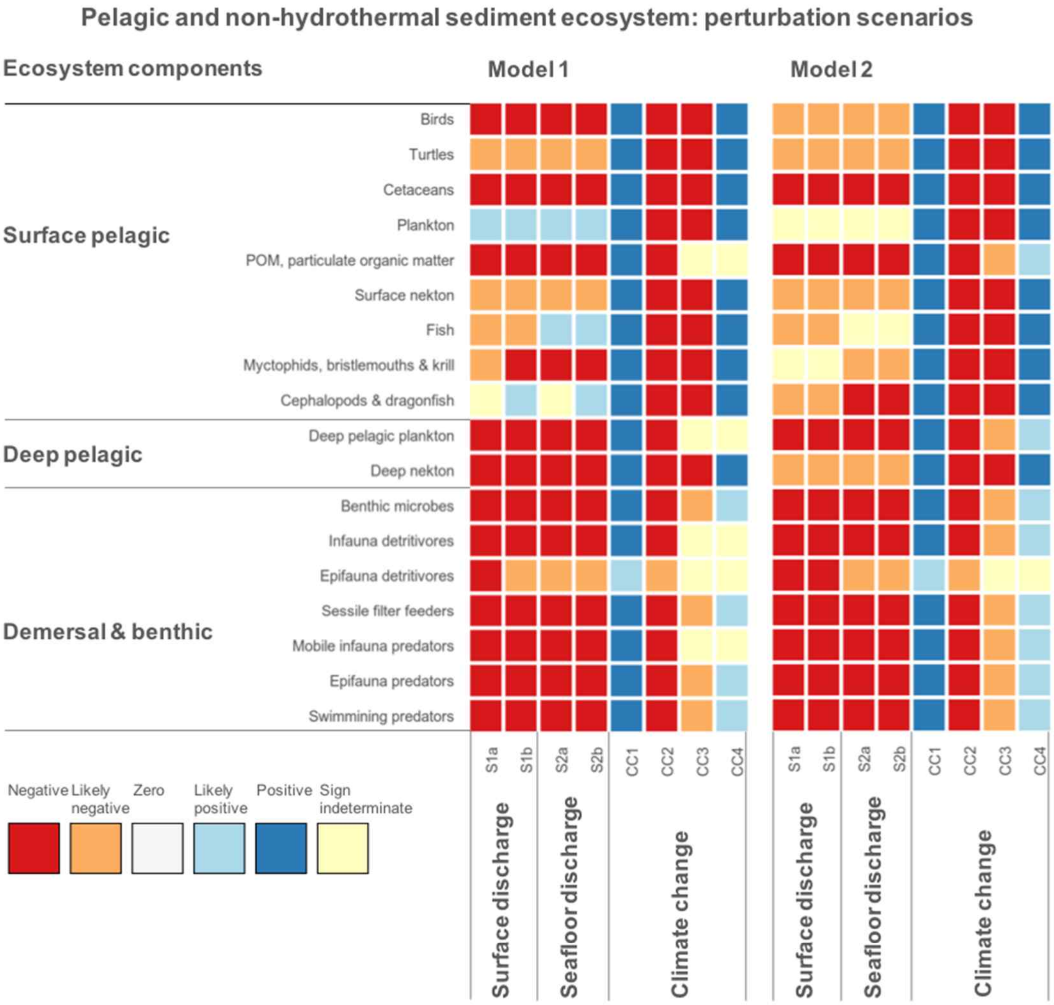
Birds, deep nekton, surface nekton and turtles were all predicted to have likely negative responses to each exploitation scenario. Fish were predicted to have likely negative responses to Scenario 1a and 1b where return water discharge was at the surface and sign indeterminate responses to Scenario 2a and 2b where return water discharge was at or near the seafloor. Myctophids, bristlemouths and krill were predicted to have likely negative responses to Scenario 2a and 2b where return water discharge was at or near the seafloor and sign indeterminate responses to Scenario 1a and 1b where return water discharge was at the surface.

Climate change scenarios

Climate change scenarios: Outcomes for Model 1 and Model 2

In both Model 1 and Model 2 (Figure 5), the climate change scenario that was predicted to be the most negative overall for a greater number of ecosystem components was CC2 where increased temperature had a negative effect on primary production of plankton and on the food quality of Particulate Organic Matter (POM). In Scenario CC2, all ecosystem components were predicted to have a certain negative response, apart from epifauna detritivores, which were predicted to have a likely negative response in both Model 1 and Model 2. In both Model 1 and Model 2, the climate change scenario that was predicted to be most positive overall for the greatest number of ecosystem components was CC1, where increased temperature had a positive effect on primary production of plankton and the food quality of POM.

The only differences between Model 1 and Model 2 were a greater number of predicted sign indeterminate (uncertain) responses for climate change scenarios CC3 and CC4 in Model 1 (5 out of 18) compared to Model 2 (1 out of 18). Model 1 included the benefits of POM consumption by sessile filter feeders and the control of cephalopod and dragon fish populations by cetaceans, whereas these links were omitted from Model 2. In CC3, there was a positive effect on POM and a negative effect on primary production, whereas in CC4, there was a positive effect on primary production and a negative effect on POM. The ecosystem components that were predicted to have sign indeterminate responses in Model 1 for both CC3 and CC4 were POM, deep pelagic plankton, epifauna detritivores, infauna detritivores, and mobile infauna predators. In Model 2, POM, deep pelagic plankton, infauna detritivores, and mobile infauna predators were predicted to have likely positive responses to CC4, where there was a positive effect on primary production, and likely negative responses to CC3, where there was a negative effect on primary production. Epifauna detritivores was the only ecosystem component in Model 2 predicted to have a sign indeterminate response to CC3 and CC4. All other ecosystem components were predicted to have the same response to CC3 or CC4 in both Model 1 and Model 2. Benthic microbes, sessile filter feeders, epifauna predators, and swimming predators were all predicted to have likely negative responses to CC3, where there was a negative effect on primary production, and likely positive responses to CC4, where there was a positive effect on primary production. Birds, turtles, cetaceans, plankton, surface nekton, fish, myctophids bristlemouths and krill, cephalopods and dragonfish, and deep nekton were all predicted to have certain negative responses to the negative effect on primary production in CC3 and certain positive responses to the positive effect on primary production in CC4.



Pressure category	Abbreviation	Perturbation scenario description	Pressure combinations
Surface discharge	S1a	Surface discharge, positive light effect	P3, P4 – P9, P11 – P13
	S1b	Surface discharge, negative light effect	P3inv, P4 – P9, P11 – P13
Seafloor discharge	S2a	Seafloor discharge, positive light effect	P3, P4 – P8, P10, P11, P13
	S2b	Seafloor discharge, negative light effect	P3inv, P4 – P8, P10, P11, P13
Climate change	CC1	Positive effect POM quality and primary production	P1, P2
	CC2	Negative effect POM quality and primary production	P1inv, P2inv
	CC3	Positive effect POM quality, negative effect primary production	P1, P2inv
	CC4	Negative effect POM quality, positive effect primary production	P1inv, P2

Figure 5. Qualitative response predictions of cumulative impacts to pelagic and non-hydrothermal sediment ecosystem components (rows) of Model 1 and Model 2 from exploitation activities or climate change (columns) in the perturbation scenarios detailed in Table 4. See Figure 2 for the signed digraph of Model 1 and Model 2.

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Annex IV Qualitative Mathematical Models for Assessing Cumulative Impacts from Future Exploitation of Polymetallic Sulphides on Hydrothermally Active Habitats of the Mid-Atlantic Ridge

Overview

- A qualitative mathematical ecosystem model for hydrothermally active habitats on the Mid-Atlantic Ridge (MAR) was created through expert elicitation. Potential pressures on this ecosystem model were described for future mineral exploitation activities.
- Three polymetallic sulphide (PMS) exploitation scenarios were considered to test the applicability of the modelling approach. Each scenario involved the disaggregation of a single PMS deposit on the seafloor and collection of material to be transported to the surface. The three scenarios differed in the type of PMS deposit exploited (hydrothermally active or inactive) and whether the PMS deposit to be exploited was in the same vent field as the hydrothermal vent habitat where impacts were to be observed. For each PMS exploitation scenario, it was assumed that the habitat at the mined site would be completely removed and that perturbations to ecosystem processes would only be modelled beyond the immediate footprint of the mined area.
- A suite of 10 pressure effects from potential future PMS exploitation activities were assessed for the 21 ecosystem components (5 physical and 16 biological) in the model.
- The individual PMS exploitation pressure with the greatest number of predicted negative responses across all ecosystem components in the model was where exploitation activities reduced the subsurface connectivity of fluid flow within the hydrothermal vent field. For many of the individual exploitation pressures considered, the biological components exhibited a high degree of uncertainty in the type of predicted response to these pressures. More information on the nature of exploitation pressures, and the biological response to these pressures, would be needed to reduce uncertainty in predicted responses.
- When potential exploitation pressures were considered together in perturbation scenarios, the two perturbation scenarios that were the most negative overall for the greatest number of ecosystem components at the unmined hydrothermally active habitat were where exploitation activity reduced the subsurface connectivity of fluid flow within the vent field. The ecosystem components in the model had the same response to this reduction in subsurface connectivity, irrespective of whether it was a hydrothermally active or a hydrothermally inactive PMS deposit that was exploited.
- The perturbation scenario that was the least negative overall for the greatest number of ecosystem components at the observed unmined hydrothermally active habitat was where exploitation occurred at a hydrothermally active PMS deposit in a different vent field. Where exploitation occurred within the same vent field, fewer negative responses from ecosystem components were predicted where subsurface connectivity was not impacted.

Background to the modelling exercise

The purpose of this modelling exercise was to describe potential impacts from the exploitation of polymetallic sulphide (PMS) deposits created through hydrothermal activity along the Mid-Atlantic Ridge (MAR).

The concept of a 'cumulative impact' can have different meanings according to the setting and context in which it is used. For the purpose of the modelling exercise, two levels of cumulative impacts were considered. The first was where a single pressure can have a cumulative impact across multiple ecosystem components in the model. In this case, the impact from the initial direct pressure on one ecosystem component was propagated to other ecosystem components through the web of interactions established in the model. The second level of cumulative impact considered was where multiple individual pressures were combined into perturbation scenarios. The direct effect of these cumulative impacts on individual ecosystem components was again propagated to other components through the model. Cumulative impacts relating to the exploitation activities of multiple contractors or multiple ocean industry sectors within a region were not explored in this modelling exercise.

The cumulative impacts assessed through the modelling exercise were qualitative, with experts assigning the direction (positive or negative) of ecosystem component response to pressures. There was insufficient information available to put weights or values on ecosystem component responses, which would be needed to develop quantitative models. Instead, qualitative mathematical models encoded as signed directed graphs (signed digraphs) were used to describe how key linkages amongst ecosystem components of the hydrothermally active vent ecosystem could be impacted under several ecosystem structure and PMS exploitation scenarios. Signed digraphs provided a qualitative depiction of variables in the ecosystem and the structure of the relationships by which they are linked. Positive effects and processes that cause the increase of a variable (e.g., a rate of reproduction or a rate of addition) were depicted by a link ending in an arrow; negative effects (e.g., a rate of mortality or a rate of removal) were shown by links ending in a filled circle.

The construction of the model began by defining a focus based on the operational scale of exploitation activities with respect to the ecosystem associated with hydrothermally active habitats on the MAR. Participants were asked to describe essential components, processes and factors associated with this ecosystem, independent of the influence of any potential exploitation activities, with an emphasis on key functional aspects. Following the construction of the ecosystem model, the next step was to describe how different pressures associated with future mineral exploitation activities could possibly affect the ecosystem. These pressures were detailed as positive or negative inputs to specific components of the signed digraph model.

Detailed methodology for the qualitative mathematical modelling approach utilized in this exercise is available in ***Annex II: Methodology for Qualitative Mathematical Modelling for Assessing Cumulative Impacts.***

Hydrothermally active habitat ecosystem model

Definitions of the ecosystem components and representative images of these components are provided in Table 1 and Figure 1 respectively. The signed digraph for the ecosystem model is provided in Figure 2 and detailed information for the individual linkages within the model is provided in Table 2.

The ecosystem model for hydrothermally active habitat only considered the habitat provided by the hydrothermally active polymetallic sulphide (PMS) deposit, not sediment habitat or any flow through cracks in basalt as observed in other ridge systems. The hydrothermal ecosystem is defined here as the physical fluid flows, biotic components and energy flows that are associated directly with the hydrothermal vent habitat. This model is intended to be interpreted as a ‘generic’ hydrothermal vent ecosystem on the northern Mid-Atlantic Ridge and was developed at the level of a vent field, where individual hydrothermally active sites are connected through sub-seafloor fluid flow (*sensu* Jamieson & Gartman 2020).

Hydrothermal vent fluids are rich in chemical resources that help to fuel primary production by chemosynthetic bacteria. Some of these bacteria are free-living in the environment, for example on hard surfaces, within sediments and in-between sulphides, and suspended within diffuse-flow and focused flow (black smoker) hydrothermal vent plumes (Dick, 2019). Other bacteria are in a symbiotic relationship with benthic organisms, referred to in the model as symbiotrophs, such as mussels and shrimp (Table 2, Figure 2). At northern Mid-Atlantic Ridge hydrothermal vents, warm diffuse vent flows (up to approximately 40°C) are occupied by the hydrothermal vent shrimp *Rimicaris exoculata* and their associated symbiotic bacteria. Cooler diffuse flows (a few degrees above ambient, 1 - 2°C) are occupied by the hydrothermal vent mussels *Bathymodiolus azoricus* or *B. puteoserpentis*, with both species being present at species hybridization zones on the ridge (Desbruyères et al., 2001; O’Mullan et al., 2001). Although an abundant population of vesicomyid clams hosting symbiotic bacteria is known from the Logatchev site on the northern Mid-Atlantic Ridge (Gebruk et al., 2000), these clams are not included in the ‘generic’ model described here.

Particulate Organic Matter (POM) in the hydrothermal vent ecosystem is chemosynthetically generated by suspended microorganisms in focused flows and by suspended and attached microorganisms in diffuse flow environments. An additional source of POM is from photosynthetically derived marine snow, assumed here to be minor in bulk mass but important in terms of supplying essential nutrients not available from the chemosynthetic microbial system (Colaço et al., 2009; Riou et al., 2010). Chemosynthetic bacteria, with a minor input from marine snow, sustain populations of symbiotrophs (shrimp and mussels discussed above), grazers (e.g. snails), suspension feeders (e.g. some polychaete worms), detritivores (e.g. some polychaetes, copepods and nematodes), predators and scavengers (e.g. crabs, some shrimp, anemones, fish) (Sievert & Vetriani, 2012). For the model developed here (Table 2, Figure 2), 'detritivores' includes deposit feeders. Scavengers and predators are grouped as a single component based on the difficulty in determining the relative contributions of different feeding modes when facultative feeding modes are possible (Colaço et al., 2002). Future cumulative impact modelling exercises may refine the ecosystem model presented here using other existing food-web models and new knowledge (Bergquist et al., 2007; Colaço et al, 2002, 2007; Portail et al., 2018; Van Dover 2002).

Population connectivity in a metapopulation framework (Vrijenhoeck, 2010) and source-sink dynamics were also considered in the ecosystem model. It was not possible to address population connectivity for all species individually. Instead, potential population linkages with other occurrences of hydrothermally active habitat were captured by model variables functioning as pools of 'vent biota reproductive output' and 'exogenous dispersal stages of vent species' (Figure 2, Table 2).

Some linkages were not included in the model because they tied a fast subsystem to the slower population-level subsystem and would also introduce a positive feedback loop that could decrease model stability and determinacy of model predictions of perturbation response. Examples of these excluded linkages were biogeochemical cycling by sulphide microorganisms and the contribution of living organisms to POM of chemosynthetic origin. Sulphide microorganisms can modify warm and cool diffuse flow chemistry through biogeochemical cycling, for example ammonia and methane generation, however these microorganisms also rely on chemical components within the warm and cool diffuse flow for chemoautotrophy and heterotrophy. Living organisms contribute to the pool of POM from chemosynthetic origin, for example through exuviates and faecal matter, but to avoid a positive feedback loop, only outward connections between POM from chemosynthetic origin and living organisms were included, for example, the consumption of this POM by mussel symbiotrophs, shrimp symbiotrophs, suspension feeder and detritivores.

A series of assumptions was made in the creation of the ecosystem model relating to physical fluid flow connections and biological components. For fluid flow, it was assumed that the total fluid flux within a vent field was fixed. Warm diffuse flow, black smoker plumes and cool diffuse flows were linked to focused flow but only indirectly linked to one another. It was assumed that a reduction in warm diffuse flow would lead to an equal and concomitant increase in cool diffuse flow and vice versa. Engaging the expertise of hydrologists would enable more complex changes in hydrothermal fluid flux to be considered in future modelling exercises. For the biological components, positive self-effects, such as those that might be associated with aggregated populations and gregarious settlement are not depicted in the model, although they are expected to occur. Facilitation and inhibition through species interactions are not considered, other than direct links to food sources and the positive effect of mussel bed structure. Species-specific thermal niches are not detailed within the model. Although a role of Dissolved Organic Material (DOM) in nutrition of vent taxa is expected, DOM was not evaluated and is not included as a model component.

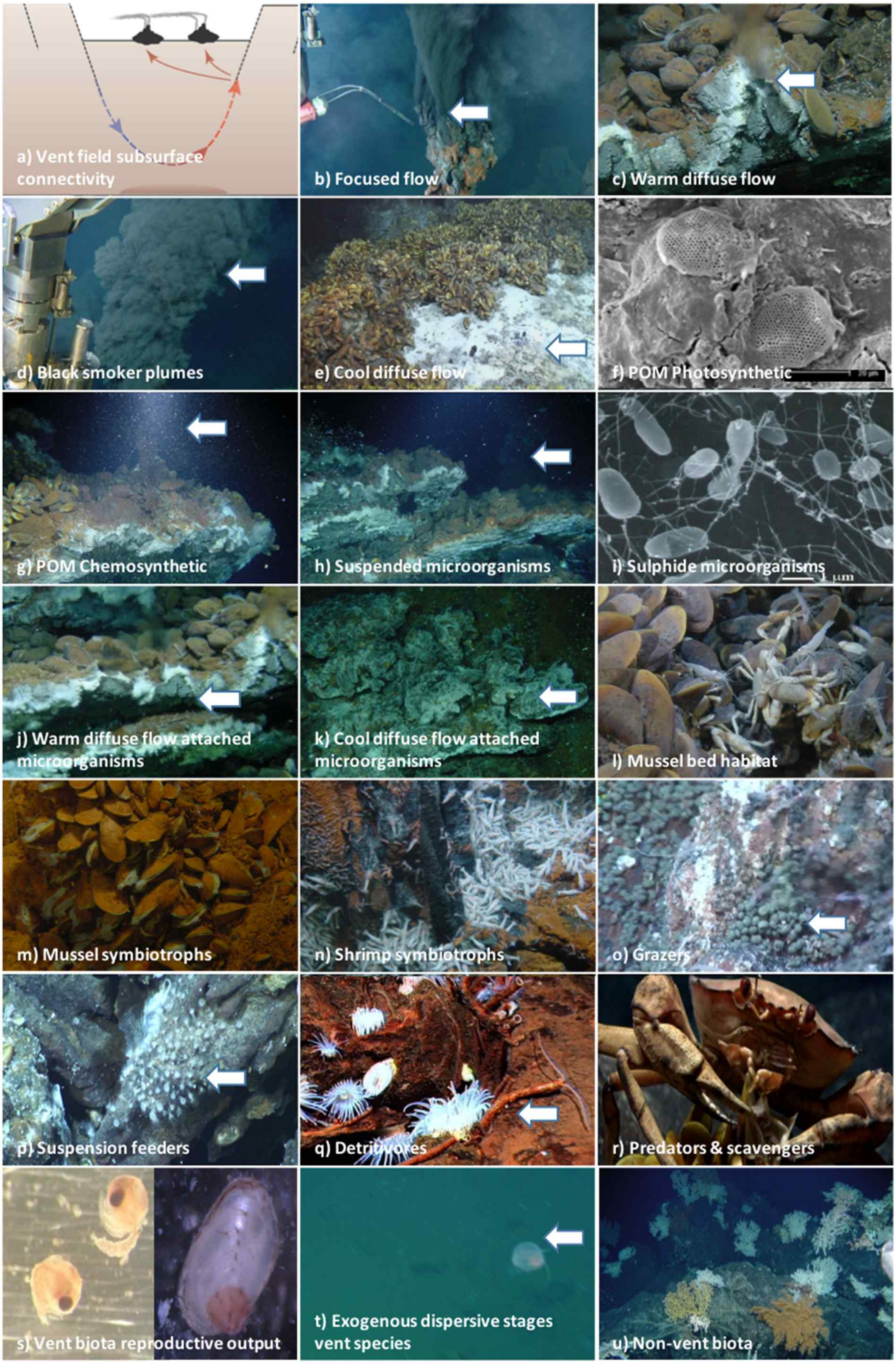
Polymetallic sulphide habitats on the Mid-Atlantic Ridge can also occur where hydrothermal activity has ceased. Following Jamieson and Gartman (2020), hydrothermally inactive (dormant) polymetallic sulphides are sites where hydrothermal activity has ceased but sub-seafloor fluid connections remain with hydrothermally active sites within the same vent field; hydrothermally extinct polymetallic sulphides are sites where hydrothermal activity has ceased and there are no sub-seafloor fluid flow connections with hydrothermally active sites. Inactive sites, by this definition could become active again in the future. Extinct sites cannot be reactivated. The modelling exercise conducted here did not attempt to construct an ecosystem model for hydrothermally inactive or extinct sites because knowledge of the biological communities at such sites on the northern Mid-Atlantic Ridge is scarce. From the information currently available, microbial communities at hydrothermally inactive sites are distinct from those at hydrothermally active sulphide habitat, surrounding sediments and hard substrate (reviewed in Van Dover 2019). Far less is known about the meio-, macro- and megafauna at hydrothermally inactive or extinct habitats on the northern Mid-Atlantic Ridge, although studies from other ocean regions suggest that the metazoan faunal communities at these habitats may also be different from those at other habitats in the region (reviewed in Van Dover 2019).

The ecosystem model presented here is intended to be a ‘generic’ hydrothermal vent ecosystem on the northern Mid-Atlantic Ridge and may not be applicable to all hydrothermal vent sites on the Mid-Atlantic Ridge, where additional ecosystem components and linkages may be present.

Table 1. Description of components included in the Mid-Atlantic Ridge hydrothermal vent ecosystem model.

Variable name	**Description**
Vent field subsurface connectivity	Subsurface hydrological connections (subsurface plumbing) shared between/among sulphide occurrences in a vent field.
Focused flow	End-member fluid (~350C+) emitted from black smoker chimneys and the resulting buoyant and neutrally buoyant plumes.
Warm diffuse flow	Higher up on a chimney relative to cool flows and/or >~15C; shrimp habitat.
Black smoker plumes	The buoyant and neutrally buoyant particle-laden fluids from black smoker (active) chimneys. Particles are predominantly very fine-grained sulphide minerals formed when the hot hydrothermal fluids mix with near-freezing seawater.
Cool diffuse flow	Lower down on a chimney relative to warm flows and/or associated with fissures, <15C; mussel habitat
Particulate organic matter photosynthetic (POM$_P$)	Non-living organic material generated through photosynthetic processes (marine snow).
Particulate organic matter chemosynthetic (POM$_C$)	Non-living organic material generated through chemoautotrophic processes (dead cells, faeces, etc).
Suspended microorganisms	Microorganisms in the water column.
Sulphide microorganisms	Microorganisms within sulphide accumulations/deposits.
Warm diffuse flow attached microorganisms	Bacterial mats and other free-living microorganisms on surfaces with warm diffuse flow.
Cool diffuse flow attached microorganisms	Bacterial mats and other free-living microorganisms on surfaces with cool diffuse flow.
Mussel bed habitat	3-dimensional habitat created by mussels, refuge for numerous small invertebrate types
Mussel symbiotrophs	The mussel and its symbionts.
Shrimp symbiotrophs	The shrimp *Rimicaris exoculata* and its symbionts.
Grazers	Selective and non-selective grazers on living microorganisms.
Suspension feeders	Reliant on suspended organisms for nutrition.
Detritivores	Non-selective feeders on detritus (may be POM$_c$ or POM$_p$) that accumulates on surfaces. Includes deposit feeders.
Predators & scavengers	Omnivorous, opportunist organisms that may be selective (e.g. *Miricaris rimicarivora*) or non-selective (e.g., bythograeid crabs that are predators and scavengers and as opportunists, even graze on bacteria).
Vent biota reproductive output	Eggs and larvae of species endemic to hydrothermal vent habitats
Exogenous dispersive stages of vent species	Larvae, juvenile, or adult life history stages that disperse in the water column.
Non-vent biota	Background non-vent benthic organisms found at other habitats in the region.

Below: Figure 1. Images of representative examples from each of the ecosystem components in the model. Physical components: a) vent filed subsurface connectivity; b) focused flow; c) warm diffuse flow; d) black smoker plumes; e) cool diffuse flow. Biological components: f) POM photosynthetic; g) POM chemosynthetic; h) suspended microorganisms; i) sulphide microorganisms; j) warm diffuse flow attached microorganisms; k) cool diffuse flow attached microorganisms; l) mussel bed habitat; m) mussel symbiotrophs; n) shrimp symbiotrophs; o) grazers; p) suspension feeders; q) detritivores; r) predators & scavengers; s) vent biota reproductive output; t) exogenous dispersive stages vent species; u) non-vent biota. Image Credits: Cropped section of Figure 3 in this report (a); SEAHMA - PDCTM/MAR/15281/1999 (b – e, g, h, j – n, r & t); Colaço (f & s); Ifremer- Momarsat 2017 (o & p); Mark Amend -NOAA Photo Library (i); CLVD and HOV Alvin/Woods Hole Oceanographic Institution (q).


a) Vent field subsurface connectivity
b) Focused flow
c) Warm diffuse flow
d) Black smoker plumes
e) Cool diffuse flow
f) POM Photosynthetic
g) POM Chemosynthetic
h) Suspended microorganisms
i) Sulphide microorganisms
j) Warm diffuse flow attached microorganisms
k) Cool diffuse flow attached microorganisms
l) Mussel bed habitat
m) Mussel symbiotrophs
n) Shrimp symbiotrophs
o) Grazers
p) Suspension feeders
q) Detritivores
r) Predators & scavengers
s) Vent biota reproductive output
t) Exogenous dispersive stages vent species
u) Non-vent biota

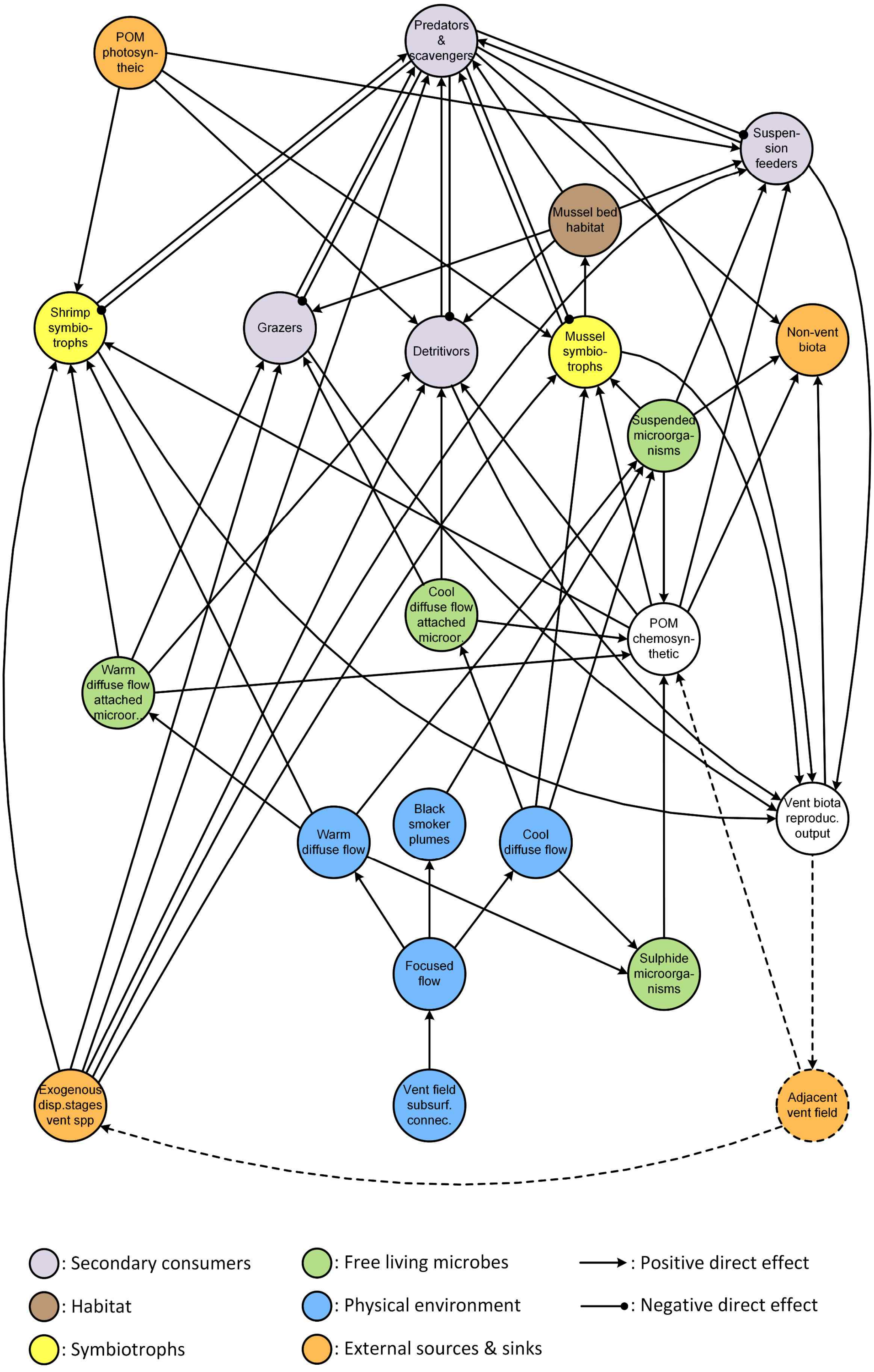


Figure 2. Signed digraph of hydrothermal vent ecosystems of the Mid-Atlantic Ridge. Each circle depicts a system variable and links positive or negative direct effects. Dashed-line links and variables associated with adjacent vent field system shown here for context but not included in analysed model; their influence is addressed as perturbation effects in Table 3.

Table 2. Ecosystem interactions of functional groups and physico-chemical components of a 'typical' hydrothermal vent ecosystem on the Mid-Atlantic Ridge (Figure 2). Effects are positive (←) or negative (•—) in sign. The hydrothermal system is assumed to be stable and without natural disturbance (e.g., capping, change in distribution of fluid flow).

Effect to	**Effect sign**	**Effect from**	**Description**	**Reference**
Focused flow	←	Vent field subsurface connectivity	Focused flow is supplied by the sub-seafloor flow through conduits that feed a hydrothermal vent field.	Jamieson & Gartman (2020)
Warm diffuse flow	←	Focused flow	Warm diffuse flow forms from convective (mixing) and conductive cooling of focused flow, creating warm diffuse flow. Warm diffuse flow is discrete, related to the extent of mixing and cooling on a chimney and does not cool to create cool diffuse flow. Warm diffuse flow ~15 to 40°C.	Bemis et al. (2012), Ravaux et al. (2019)
Black smoker plumes	←	Focused flow	The hot end-member focused flow fluid emitted from black smoker chimneys (~350°C+) creates particle-laden buoyant and neutrally buoyant black smoker plumes.	Rudnicki & Elderfield (1993).
Cool diffuse flow	←	Focused flow	Cool diffuse flow forms from convective (mixing) and conductive cooling of focused flow, creating cool diffuse flow. Cool diffuse flow is discrete, related to the mixing and cooling on a chimney. Cool diffuse flow occurs lower down a chimney relative to warm diffuse flow. Cool diffuse flow less than ~15°C.	Bemis et al. (2012)
Particulate organic matter chemosynthetic (POM_C)	←	Sulphide microorganisms, suspended microorganisms, warm diffuse flow attached microorganisms and cool diffuse flow attached microorganisms	Sulphide microorganisms, suspended microorganisms, warm diffuse flow attached microorganisms and cool diffuse flow attached microorganisms provide chemosynthetically derived non-living organic material to suspended particulate organic material.	Portail et al. (2018).
Suspended microorganisms	←	Warm diffuse flow, black smoker plume, cool diffuse flow	Warm diffuse flow, black smoker plume and cool diffuse flow provide substances to support chemoautotrophy and heterotrophy.	Holden et al. (2012), Wirsen et al. (1993), Bennett et al. (2013), Reed et al. (2015).
Sulphide microorganisms	←	Warm diffuse flow, cool diffuse flow	Warm and cool diffuse flows provide the physical and chemical environments to support chemoautotrophy and heterotrophy.	Holden et al. (2012), Le Bris et al. (2019), Scott et al. (2015), Wirsen et al. (1993).
Warm diffuse flow attached microorganisms	←	Warm diffuse flow	Warm diffuse flows provide the physical and chemical environments to support chemoautotrophy and heterotrophy.	Holden et al. (2012), LeBris et al. (2019), Wirsen et al. (1993).
Cool diffuse flow attached microorganisms	←	Cool diffuse flow	Cool diffuse flows provide the physical and chemical environments to support chemoautotrophy and heterotrophy.	Holden et al. (2012), LeBris et al. (2019), Wirsen et al. (1993).
Mussel bed habitat	←	Mussel symbiotrophs	Mussel symbiotrophs create the mussel bed habitat.	Expert opinion
Mussel symbiotrophs	←	Cool diffuse flow	Cool diffuse flow provides the inorganic nutrients (e.g. H_2S, CH_4, H_2, Fe^{2+}, CO_2) to support chemosynthesis of microbes in symbiosis with mussels.	Colaço et al. (2002).

Effect to	Effect sign	Effect from	Description	Reference
Mussel symbiotrophs	←	POM$_P$	POM$_P$ provides essential dietary items (e.g., specific amino acids) and heterotrophic nutrition for the mussels in symbiosis with microbes.	Colaço et al. (2009), Riou et al. (2010).
Mussel symbiotrophs	←	Suspended microorganisms, POM$_C$	Suspended microorganisms and POM$_C$ provide heterotrophic nutrition for the mussels in symbiosis with microbes.	Colaço et al. (2009).
Shrimp symbiotrophs	←	Warm diffuse flow	Warm diffuse flow provides the inorganic nutrients (e.g. H_2S, CH_4, H_2, Fe^{2+}, CO_2) to support chemosynthesis of microbes in symbiosis with shrimp.	Colaço et al. (2002), Gebruk et al. (2000), Govenar (2012).
Shrimp symbiotrophs	←	POM$_P$	POM$_P$ provides essential dietary items (e.g., specific amino acids) and heterotrophic nutrition for the shrimp in symbiosis with microbes.	Gebruk et al. (2000).
Shrimp symbiotrophs	←	Warm diffuse flow attached microorganisms, POMc	Warm diffuse flow attached microorganisms provide heterotrophic nutrition for the shrimp in symbiosis with microbes.	Gebruk et al. (2000), Zbinden et al. (2004, 2008, 2017).
Grazers, detritivores, suspension feeders, predators & scavengers	←	Mussel bed habitat	Mussel bed habitat provides refuge for organisms and ameliorate the environment.	Fisher et al. (2007), Husson et al. (2016), Rybakova and Galkin (2015), Van Dover & Trask (2000), Van Dover et al. (2005).
Grazers	←	Warm diffuse flow attached microorganisms and attached cool diffuse flow microorganisms	Warm diffuse flow attached microorganisms and cool diffuse flow attached microorganisms provide heterotrophic nutrition for grazers.	Colaço et al. (2006, 2007).
Suspension feeders	←	POM$_P$	POM$_P$ provides essential dietary items (e.g., specific amino acids) and heterotrophic nutrition for suspension feeders.	Colaço et al. (2009), Riou et al. (2010).
Suspension feeders	←	Suspended microorganisms, POM$_C$	Suspended microorganisms and POM$_C$ provide heterotrophic nutrition for suspension feeders.	Colaço et al. (2009), LeBris et al. (2019), Riou et al. (2010).
Detritivores	←	POM$_P$	POM$_P$ provides essential dietary items (e.g., specific amino acids) and heterotrophic nutrition for detritivores.	Zeppilli et al. (2018).
Detritivores	←	Warm diffuse flow attached microorganisms, attached cool diffuse flow microorganisms and POM$_C$	Warm diffuse flow attached microorganisms, cool diffuse flow attached microorganisms and POM$_C$ provide heterotrophic nutrition for detritivores.	Colaço et al. (2006), Colaço et al. (2007), Portail et al. (2018), Zeppilli et al. (2018).
Predators & scavengers	←	Mussel symbiotrophs, shrimp symbiotrophs, grazers, suspension feeders, detritivores	Mussels, shrimp symbiotrophs, grazers, suspension feeders and detritivores provide heterotrophic nutrition for predators & scavengers. Predators can be facultative scavengers.	Colaço et al. (2002, 2007), Fabri et al. (2011), Portail et al. (2018).
Mussel symbiotrophs, shrimp symbiotrophs, grazers, suspension feeders and detritivores	•—	Predators & scavengers	Predators act as population controls for mussel symbiotrophs, shrimp symbiotrophs, grazers, suspension feeders and detritivores. Predators can be facultative scavengers.	Colaço et al. (2002), Fabri et al. (2011), Portail et al. (2018).
Mussel symbiotrophs, shrimp symbiotrophs, grazers, suspension	←	Exogenous dispersive stages of vent species	Exogenous dispersive stages of vent species are imported from other vent fields or sites within the same vent field to the ecosystem providing potential recruits to all benthic	Teixeira et al. (2011, 2012), Vrijenhoek et al. (2010).

Effect to	Effect sign	Effect from	Description	Reference
feeders, detritivores, predators & scavengers			vent species populations. Dispersive stages include larvae, juveniles and mobile adults.	
Vent biota reproductive output	←	Mussel symbiotrophs, shrimp symbiotrophs, grazers, suspension feeders, detritivores, predators & scavengers	Mussels, shrimp symbiotrophs, grazers, suspension feeders and detritivores contribute to the vent biota reproductive output pool.	Expert opinion.
Non-vent biota	←	Predators & scavengers	Vent predators & scavengers provide heterotrophic nutrition to marauding non-vent predators, e.g. octopods and fish.	Colaço et al. (2002), Levin et al. (2016).
Non-vent biota	←	Suspended microorganisms	Suspended microorganisms export production from the hydrothermal vent biota to be consumed by non-vent biota.	Molodstova et al. (2017), Levin et al. (2016).
Non-vent biota	←	POM$_C$	POM$_C$ provides heterotrophic nutrition for non-vent biota.	Expert opinion.
Non-vent biota	←	Vent biota reproductive output	Vent reproductive output exports production from the hydrothermal vent biota is consumed by non-vent biota.	Colaço et al. (2006), Dixon et al. (2006), Hilario et al. (2015), Ramirez-Llodra et al. (2000), Vrijenhoek et al. (2010).

Pressures on the ecosystem model

Future polymetallic sulphide exploitation

Potential pressures to this ecosystem were described for future PMS exploitation on the northern MAR (Tables 3a - d). Potential pressures associated with climate change or ocean acidification were not considered during this exercise. It was assumed that exploitation of a single PMS deposit would completely remove the entire metazoan community within the footprint of the mineral extraction (Van Dover et al., 2018; Van Dover 2014). Hydrothermal fluid flow was expected to continue after exploitation, meaning that chemosynthetically derived POM would persist beyond the period of exploitation activities, although the majority of microbial biomass will probably be removed with the mineral resource that it had colonised (Orcutt et al., 2020). Because almost all of the components of the hydrothermal vent ecosystem would be removed by mineral extraction, conducting a perturbation analysis of the model system at the mined site would be uninformative. However, where pressures were considered to have effects beyond the immediate exploitation footprint, the impacts on the model hydrothermal vent ecosystem in those locations were assessed.

Pressures were only considered where expert elicitation determined there was potential for sustained direct, population-level effects on the ecosystem model components. More temporary or ‘pulse’ effects were not considered. For example, if mobile predators were to migrate from the unmined site to the mined site to feed on organisms that were injured or killed by exploitation, this would be a short-term effect (pulse) that is outside the scope of the model. Indirect effects on ecosystem components were captured through interactions detailed in the ecosystem model. Recovery dynamics and recolonization patterns were not included in this perturbation analysis because succession in MAR hydrothermal vent ecosystems is poorly understood.

The list of potential pressures from exploitation activities that was used for this modelling exercise was modified from Washburn et al. (2019). Only those pressures that related to extraction of PMS deposits at the seafloor were considered here. It was assumed that the plume generated by PMS deposit extraction at the seafloor may extend to other occurrences of hydrothermally active habitat within the same vent field but would not extend beyond the vent field where exploitation activities occurred. Exploitation pressures considered included habitat removal, changes (increases or decreases) to hydrothermal fluid flow, altered hydrography, organism burial, clogging of suspension-feeding and inhibition of function of respiratory structures, plume toxicity, increased light, increased sound and vibration, and electromagnetic radiation. The potential direct population-level effects of some of these pressures could not be scored within the framework of this modelling exercise because of high uncertainty pertaining to the nature of these pressures and the responses of ecosystem components. The five pressures not assessed were: altered hydrography, organism burial, increased light, increased sound and vibration, and electromagnetic radiation. These pressures could be addressed in future modelling exercises when more detailed information on these pressures is available. Organism burial may be anticipated in the case of mineral exploitation, particularly where removal of sediment overburden takes place. However, only the impacts beyond the direct footprint of mineral extraction were considered, which for this exercise did not include the removal of overburden. As a result, burial of organisms was not anticipated beyond the direct footprint of mineral extraction and so was not considered further in this exercise.

For some of the scored pressures, there was uncertainty as to whether there would be direct population-level effects or whether the effects would be neutral. Within the model framework, it was only possible to assess positive or negative effects. Taking a precautionary approach, in cases where it was uncertain whether the effects would be negative or neutral, the effects were modelled as negative. As a result, the exercise presents a worst-case scenario, but one that still focuses on the potential effects deemed most likely to occur.

Polymetallic sulphide exploitation scenarios

Three exploitation scenarios were considered (Figure 3) for simplicity and to test the applicability of the approach. Each exploitation scenario involved the extraction of a single PMS deposit on the seafloor. This modelling exercise did not consider pressures associated with pumping disaggregated material to the surface; dewatering at the surface; or discharge of the return water from surface processing. It was assumed that there was no sediment overburden to be removed in any of the scenarios. Although, it was recognized that hydrothermally inactive PMS deposits may accumulate sediment that would need to be removed as part of exploitation. It was assumed that for all scenarios (see below), any fluid flow would be through sulphides and not through surrounding sediments or basalts.

- **Scenario 1**: A single hydrothermally active PMS deposit is exploited. Hydrothermal habitat at unmined locations in the same vent field may experience direct and indirect effects.
- **Scenario 2**: A single hydrothermally active PMS deposit is exploited. Hydrothermal habitat at unmined locations in a different vent field may experience direct and indirect effects.
- **Scenario 3**: A single hydrothermally inactive PMS deposit is exploited. There is the potential for the exploited hydrothermally inactive PMS deposit to reactivate and become hydrothermally active. Hydrothermal habitat at unmined locations in the same vent field may experience direct and indirect effects.

These exploitation scenarios do not apply strict temporal and spatial boundaries, as the precise spatiotemporal scales of potential impacts from exploitation on the MAR remain unknown to date. For the temporal scale, only perturbations that would lead to a long-term shift in ecosystem state were considered. Perturbations included in the model were considered to have the potential for multi-year or decadal effects.

For the spatial scale, perturbations were assessed in the immediate environment of their effects (pseudo site-scale) and not across the region as a whole. Where mining occurred within the same vent field as the unmined hydrothermally active habitat where impacts were to be observed, it was assumed that these sites were sufficiently close for plume related impacts, such as clogging and toxicity, to reach the unmined site. There is very little information available on the particle or chemical properties of plumes from exploitation activities on the MAR. As a result, the direct effects scored in Tables 3 – 5 were considered worst case scenarios, in keeping with a precautionary approach. Greater certainty on the spatiotemporal scales of potential impacts from exploitation would enable more precise spatial and temporal boundaries to be applied in future modelling exercises.

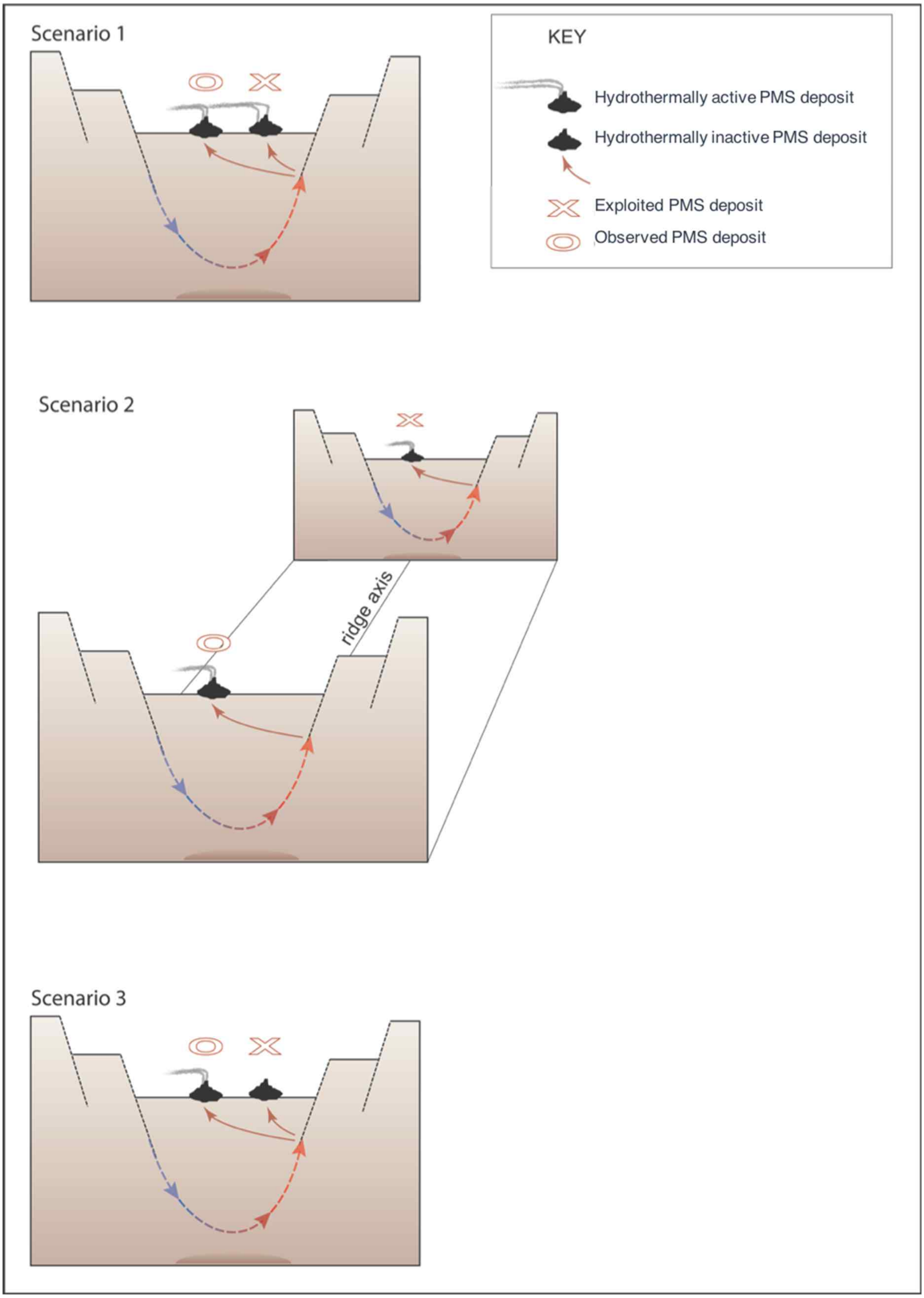


Figure 3. Mine site location and assessment areas for four perturbation scenarios in cumulative impact assessment of hydrothermal vent ecosystems of the Mid-Atlantic Ridge. Images adapted from Jamieson and Gartman (2020).

Table 3. Potential pressures and effects from exploitation activities on hydrothermally active ecosystems of the Mid-Atlantic Ridge for **Scenario 1**, where a hydrothermally active deposit is exploited within the same vent field as the unmined hydrothermally active habitat where impacts are observed. The potential pressures presented are either positive or negative in their action on components of Figure 2. The effects detailed in the table are based on expert knowledge together with published knowledge for hydrothermal vent ecosystems and related organisms.

Pressure	Pressure effect	Direct effect on	Description	Reference
Habitat removal	P1) negative	Exogenous dispersive stages of vent species including shrimp, mussel, grazers, detritivores, suspension feeders, predators and scavengers	Removal of hydrothermal vent habitat at the mined site reduces rate of immigration of exogenous dispersive stages to the unmined site in the same vent field. Exogenous dispersive stages would have come from the mined PMS deposit or from the wider exogenous dispersal stage pool. Reduces brood stock through removing one active PMS site.	O'Brien et al. (2015), Mullineaux et al. (2018).
	P2) negative	POM chemosynthetic (POMc)	Removal of hydrothermal vent habitat at the mined site reduces the rate of delivery of exogenous chemosynthetic POM from the mined site to the unmined site in the same vent field.	Expert opinion
Hydrothermal fluid change	P3) negative	Vent field subsurface connectivity	Disturbance of the subsurface permeability network for the vent field could reduce subsurface vent field connectivity.	Expert opinion
	P4) negative	Warm diffuse flow (with positive effect on cool diffuse flow)	Disturbance of hydrothermal fluid flow could result in reduced warm diffuse flow and increase in cool diffuse flow.	Expert opinion
	P5) negative	Cool diffuse flow (with positive effect on warm diffuse flow)	Disturbance of hydrothermal fluid flow could result in reduced cool diffuse flow and increase in warm diffuse flow.	Expert opinion
Sediment clogging: clogging of suspension-feeding and inhibition of function of oxygen respiratory structures (e.g. gills)	P6) negative	Exogenous dispersive stages of vent species including shrimp, mussel, grazers, detritivores, suspension feeders, predators and scavengers.	If the active PMS deposit is completely removed during exploitation, all exogenous dispersal stages that may have come from the mined site to the unmined site are lost. Exogenous dispersal stages could subsequently come from other non-mined vent habitat within the same vent field as the mined PMS deposit. Sediment-laden plumes created during exploitation of an active PMS deposit within the same field as the unmined site could impact the pool of exogenous dispersal stages that originates in that vent field.	Cheung & Shin (2007), Farkas et al. (2017), Salas-Yanquin et al. (2018), Strachan & Kingston (2012).
	P7) negative	Adult shrimp, mussels, grazers, detritivores, suspension feeders, predators & scavengers and non-vent biota	Response depends on the quantity of particles, and particle properties, such as size and shape. The lack of information on particle properties introduces uncertainty. Scoring here reflects the worst-case scenario, if only fine particles travel to the unmined site, the effect may be smaller. The general assumption is that the effect would be from the activities of the mining vehicle at the seafloor, not from the return of material to the seafloor following dewatering at the surface.	Cheung & Shin (2007), Farkas et al. (2017), Salas-Yanquin et al. (2018), Strachan & Kingston (2012).
Plume toxicity	P8) negative	Exogenous dispersive stages of vent species including shrimp, mussel, grazers, detritivores, suspension feeders, predators and scavengers.	If the active PMS deposit is completely removed during exploitation, all exogenous dispersal stages that may have come from the mined site to the unmined site are lost. Exogenous dispersal stages could subsequently come from other non-mined vent habitat within the same vent field as the mined PMS deposit. Potentially toxic plumes created during exploitation of a PMS deposit within the same field as the unmined site could impact the pool of exogenous dispersal stages that originates in that vent field.	Hauton et al. (2017), Martins et al. (2017), Orcutt et al. (2020), Pinheiro et al. (2019).
	P9) negative	Adult shrimp, mussels, grazers, detritivores, suspension feeders, predators & scavengers and non-	Very little is known about the toxicity of plumes from PMS exploitation activities, although there is the potential for an effect. Many vent biota will	Hauton et al. (2017), Martins et al. (2017), Orcutt

Pressure	Pressure effect	Direct effect on	Description	Reference
		vent biota. POM chemosynthetic, warm diffuse flow attached microorganisms, cool diffuse flow attached microorganisms and suspended microorganisms.	have a degree of tolerance to some potentially toxic compounds as these may be present naturally in the hydrothermal vent environment. Different organisms may have niches related to the concentrations of these compounds and may have different tolerances to toxicity from plumes resulting from exploitation activity. The lack of information on plume toxicity introduces uncertainty. Scoring here reflects the worst-case scenario.	et al. (2020), Pinheiro et al. (2019).

Table 4. Potential pressures and effects from exploitation activity on hydrothermally active ecosystems of the Mid-Atlantic Ridge for **Scenario 2**, where a hydrothermally active PMS deposit is exploited in a different vent field to the unmined hydrothermally active habitat where impacts are observed. The potential pressures presented are either positive or negative in their action on components of Figure 2. The effects detailed in the table are based on expert knowledge together with published knowledge for hydrothermal vent ecosystems and related organisms.

Pressure	Pressure Effect	Direct effect on	Description	Reference
Habitat removal	P1) negative	Exogenous dispersive stages of vent species including shrimp, mussel, grazers, detritivores, suspension feeders, predators and scavengers	Removal of hydrothermal vent habitat at the mined site reduces rate of immigration of exogenous dispersive stages to the unmined site in the adjacent vent field. Exogenous dispersive stages would have come from the mined PMS deposit or from the wider exogenous dispersal stage pool. Reduces brood stock through removing one active PMS site.	O'Brien et al. (2015), Mullineaux et al. (2018).
	P2) negative	POM chemosynthetic (POMc)	Removal of hydrothermal vent habitat at the mined site reduces the rate of delivery of exogenous chemosynthetic POM from the mined site to the unmined site in the adjacent vent field.	Expert opinion
Sediment clogging: clogging of suspension-feeding and inhibition of function of oxygen respiratory structures (e.g. gills)	P6) negative	Exogenous dispersive stages of vent species including shrimp, mussel, grazers, detritivores, suspension feeders, predators and scavengers	Sediment-laden plumes created during exploitation of a PMS deposit could impact the pool of exogenous dispersal stages that originates in the same field as the mined PMS deposit. The plume itself (including any suspended sediment) would not travel to the adjacent vent field. However, the exogenous dispersal stages travelling to the adjacent field could be impacted.	Cheung & Shin (2007), Farkas et al. (2017), Salas-Yanquin et al. (2018), Strachan & Kingston (2012).
Plume toxicity	P8) negative	Exogenous dispersive stages of vent species including shrimp, mussel, grazers, detritivores, suspension feeders, predators and scavengers	If active PMS deposit completely removed during exploitation, all exogenous dispersal stages that may have come from the mined site to the unmined site are lost. Exogenous dispersal stages could subsequently come from other non-mined vent habitat within the same vent field as the mined PMS deposit. Potentially toxic plumes created from exploitation of a PMS deposit within the same field could impact the pool of exogenous dispersal stages that originates in that field. The plume itself (including any potential toxic elements) would not travel to the adjacent vent field. However, the exogenous dispersal stages travelling to the adjacent field could be impacted.	Hauton et al. (2017), Martins et al. (2017), Orcutt et al. (2020), Pinheiro et al. (2019).

Table 5. Potential pressures and effects from exploitation activities on hydrothermally active ecosystems of the Mid-Atlantic Ridge for **Scenario 3**, where a hydrothermally inactive deposit is exploited within the same vent field as the unmined hydrothermally active habitat where impacts are observed. The potential pressures presented are either positive or negative in their action on components of Figure 2. The effects detailed in the table are based on expert knowledge together with published knowledge for hydrothermal vent ecosystems and related organisms.

Pressure	**Pressure Effect**	**Direct effect on**	**Description**	**Reference**
Habitat removal	P10) negative	Non-vent biota	Non-vent biota is included in the model as these organisms benefit from export flux of the hydrothermal vent ecosystem. They may inhabit active, inactive and extinct sites. Removal of an inactive PMS deposit may remove habitat for non-vent biota.	Orcutt et al. (2020).
Hydrothermal fluid change	P3) negative	Vent field subsurface connectivity	Disturbance of the subsurface permeability network for the vent field could reduce subsurface vent field connectivity.	Expert opinion
	P4) negative	Warm diffuse flow (with positive effect on cool diffuse flow)	Disturbance of hydrothermal fluid flow could result in reduced warm diffuse flow and increase in cool diffuse flow.	Expert opinion
	P5) negative	Cool diffuse flow (with positive effect on warm diffuse flow)	Disturbance of hydrothermal fluid flow could result in reduced cool diffuse flow and increase in warm diffuse flow.	Expert opinion
Sediment clogging: clogging of suspension-feeding and inhibition of function of oxygen respiratory structures (e.g. gills)	P6) negative	Exogenous dispersive stages of vent species including shrimp, mussel, grazers, detritivores, suspension feeders, predators and scavengers.	Sediment-laden plumes created during exploitation of an inactive PMS deposit within the same field as the unmined site could impact the pool of exogenous dispersal stages that originates in that vent field.	Cheung & Shin (2007), Farkas et al. (2017), Salas-Yanquin et al. (2018), Strachan & Kingston (2012).
	P7) negative	Adult shrimp, mussels, grazers, detritivores, suspension feeders, predators & scavengers and non-vent biota	Response depends on the quantity of particles, and particle properties, such as size and shape. The lack of information on particle properties introduces uncertainty. Scoring here reflects the worst-case scenario, if only fine particles travel to the unmined site, the effect may be smaller. The general assumption is that the effect would be from the activities of the mining vehicle at the seafloor, not from the return of material to the seafloor following dewatering at the surface.	Cheung & Shin (2007), Farkas et al. (2017), Salas-Yanquin et al. (2018), Strachan & Kingston (2012).
Plume toxicity	P8) negative	Exogenous dispersive stages of vent species including shrimp, mussel, grazers, detritivores, suspension feeders, predators and scavengers.	Potentially toxic plumes created during exploitation of an inactive PMS deposit within the same field as the unmined site could impact the pool of exogenous dispersal stages that originates in that vent field.	Hauton et al. (2017), Martins et al. (2017), Orcutt et al. (2020), Pinheiro et al. (2019).
	P9) negative	Adult shrimp, mussels, grazers, detritivores, suspension feeders, predators & scavengers and non-vent biota. POM chemosynthetic, warm diffuse flow attached microorganisms, cool diffuse flow attached microorganisms and suspended microorganisms.	Very little is known about the toxicity of plumes from PMS exploitation activities, although there is the potential for an effect. Many vent biota will have a degree of tolerance to some potentially toxic compounds as these may be present naturally in the hydrothermal vent environment. Different organisms may have niches related to the concentrations of these compounds and may have different tolerances to toxicity from plumes resulting from exploitation activity. The lack of information on plume toxicity introduces uncertainty. Scoring here reflects the worst-case scenario.	Hauton et al. (2017), Martins et al. (2017), Orcutt et al. (2020), Pinheiro et al. (2019).

Perturbation combinations for pressures modelling

The ten possible pressure effects emanating from future PMS exploitation activities detailed in Tables 3 – 5 were combined into nine separate perturbation scenarios (Table 6). A very large number of pressure effect combinations (> 500) was possible in this exercise. The perturbation scenarios presented in Table 4 were selected to reflect the most parsimonious combinations of pressure effects that could be presented in a set of potential perturbation scenarios to demonstrate the approach.

For exploitation Scenario 1, where there was exploitation of a hydrothermally active PMS deposit in the same vent field as the observed unmined hydrothermally active habitat, there were four possible perturbation scenarios (S1a – S1d, Table 6). All of these perturbation combinations under Scenario 1 included the effect of habitat removal on the pool of exogenous dispersal stages of vent species (P1) and the pool of exogenous POM of chemosynthetic origin (P2); the effects of clogging of suspension-feeding structures or inhibition of function of oxygen respiratory structures on the pool of exogenous dispersal stages of vent species (P6) and adult vent and non-vent biota (P7); and the effect of plume toxicity on the pool of exogenous dispersal stages of vent species (P8) and adult vent and non-vent biota (P9). The differences between the perturbation combinations under Scenario 1 reflect the different impacts these scenarios were modelled to have on hydrothermal fluid flow within the vent field. Under S1a, exploitation of the active PMS deposit has no impact on the subsurface connectivity of hydrothermal fluid flow and the effect of a reduction in subsurface connectivity (P3) is not included. In S1b, this pressure (P3) is included, as exploitation results in reduced vent field subsurface connectivity. In S1c, subsurface connectivity is not reduced by exploitation activities, but there is a reduction in warm diffuse flow (P4). In S1d, subsurface connectivity and warm flow are not reduced, instead there is a reduction in cool diffuse flow (P5).

There was only one perturbation combination for Scenario 2 (S2, Table 6), where there was exploitation of a hydrothermally active PMS deposit in a different vent field from the observed unmined hydrothermally active habitat. In this scenario, there was no subsurface fluid flow connection between the exploited PMS deposit and observed hydrothermally active habitat, as a result the perturbation scenario does not include any pressures relating to change in fluid flow (P3 – P5). Given the separation of the t exploited PMS deposit and observed hydrothermally active habitat across two vent fields, any effects on the adult vent and non-vent biota (P7, P9) were excluded, as any plume-related impacts were not anticipated to extend beyond the vent field where exploitation occurred. The only pressures included within S2 were those relating to effects on the pool of exogenous dispersal stages of vent species (P1, P6, P8) and the effect on the pool of exogenous POM of chemosynthetic origin (P2). These effects were included because it was considered that exploitation in one vent field could have a negative effect on the external supply (exogenous) of dispersal stages of vent species and POM of chemosynthetic origin at the unmined site in a different vent field.

For exploitation Scenario 3, where there was exploitation of a hydrothermally inactive PMS deposit in the same vent field as the unmined observed hydrothermally active habitat, there were four possible perturbation scenarios (S3a – S3d, Table 6). As in Scenario 1, all of the perturbation combinations under Scenario 3 included the effects of clogging of suspension-feeding structures or inhibition of function of oxygen respiratory structures on the pool of exogenous dispersal stages of vent species (P6) and adult vent and non-vent biota (P7); and the effect of plume toxicity on the pool of exogenous dispersal stages of vent species (P8) and adult vent and non-vent biota (P9). In addition, all Scenario 3 perturbation scenarios included the effect of habitat removal on the non-vent biota (P10), as the hydrothermally inactive PMS deposit that was mined may have hosted populations of this fauna. The differences between the perturbation combinations under Scenario 3 reflect the different impacts these scenarios were predicted to have on hydrothermal fluid flow within the vent field. Under S3a, exploitation of the active PMS deposit has no impact on the subsurface connectivity of hydrothermal fluid flow and the effect of a reduction in subsurface connectivity (P3) is not included. In S3b, this pressure (P3) is included, as exploitation results in reduced vent field subsurface connectivity. In S3c, subsurface connectivity is not reduced by exploitation activities, but there is a reduction in warm diffuse flow (P4). In S1d, subsurface connectivity and warm flow are not reduced, instead there is a reduction in cool diffuse flow (P5).

Table 6. Perturbation scenarios assembled from combined effects of pressures detailed in Table 3 – 5 from future polymetallic sulphide exploitation activities on hydrothermal vent ecosystems of the Mid Atlantic Ridge.

Perturbation scenario	Pressure effect number from Table 3	Brief perturbation description
S1a	P1, P2, P6 – P9	Exploitation of a hydrothermally active PMS deposit in the same vent field with no impact to subsurface fluid flow.

Perturbation scenario	Pressure effect number from Table 3	Brief perturbation description
S1b	P1, P2, P3, P6 – P9	Exploitation of a hydrothermally active PMS deposit in the same vent field resulting in reduced subsurface fluid flow.
S1c	P1, P2, P4, P6 – P9	Exploitation of a hydrothermally active PMS deposit in the same vent field resulting in reduced warm diffuse flow and increased cool diffuse flow.
S1d	P1, P2, P5, P6 – P9	Exploitation of a hydrothermally active PMS deposit in the same vent field resulting in reduced cool diffuse flow and increased warm diffuse flow.
S2	P1, P2, P6, P8	Exploitation of a hydrothermally active PMS deposit in a different vent field. No subsurface fluid flow connections.
S3a	P6 – P9, P10	Exploitation of a hydrothermally inactive PMS deposit in the same vent field with no impact to subsurface fluid flow.
S3b	P3, P6 – P9, P10	Exploitation of a hydrothermally inactive PMS deposit in the same vent field resulting in reduced subsurface fluid flow.
S3c	P4, P6 – P9, P10	Exploitation of a hydrothermally inactive PMS deposit in the same vent field resulting in reduced warm diffuse flow and increased cool diffuse flow.
S3d	P5, P6 – P9, P10	Exploitation of a hydrothermally inactive PMS deposit in the same vent field resulting in reduced cool diffuse flow and increased warm diffuse flow.

Outcomes from the qualitative modelling exercise

The predicted responses of ecosystem components in the model to individual or multiple pressures were classified according to their probability for sign determinacy as either certain negative, likely negative, zero, likely positive, certain positive, or sign indeterminate. Certain positive or negative responses were predicted where all pathways of linkages leading from a pressure to an ecosystem component were of the same sign and the probability for sign determinacy is 100%. Zero responses were predicted where the ecosystem component had an absence of any effects being transmitted from the pressure. Likely positive or negative responses were predicted where the majority of pathways caused effects with the same sign and the probability for sign determinacy is ≥80%.

Cumulative impact single pressures

The ten individual pressures detailed in Tables 3 – 5 were used to predict the cumulative impact on the twenty-one ecosystem components (5 physical, 16 biological) in the ecosystem model (Figure 4). The predicted response of physical components in the model to exploitation pressures was closely linked to the nature of these pressures. Reduced subsurface connectivity of fluid flow within the hydrothermal vent field (P3) was predicted to result in a certain negative response for all physical components, as these are all sub-components of the total hydrothermal fluid flux in the system. A reduction in warm diffuse flow (P4) was predicted to elicit a certain positive response from cool diffuse flow (P5), and vice versa, because the pressures were designed as an equal and opposite effect on the other flow. A reduction in warm diffuse flow or cold diffuse flow, however, was designed to have no impact on vent field subsurface connectivity, focused flow and black smoker plumes.

The individual pressure with the least effect was habitat removal for non-vent biota (P10), which was only predicted to have a certain negative response for non-vent biota and zero response for all other ecosystem components. The pressure that was predicted to be the most negative overall for the greatest number of ecosystem components was where exploitation activities reduced the subsurface connectivity of fluid flow within the hydrothermal vent field. The majority of biological components were predicted to have either a certain negative response to a reduction in subsurface connectivity (8 out of 16: POM of chemosynthetic origin, suspended microorganisms, sulphide microorganisms, warm diffuse flow attached microorganisms, cool diffuse flow attached microorganisms, predators and scavengers, vent biota reproductive output, and non-vent biota) or a likely negative response (4 out of 16: mussel bed habitat, mussel symbiotrophs, suspension feeders, and detritivores). Shrimp symbionts were predicted to have a sign indeterminate (uncertain) response to reduced subsurface connectivity, whilst POM of photosynthetic origin and exogenous dispersive stages of vent species were predicted to have a zero response. The only biological component predicted to have a likely positive response to reduced subsurface connectivity was grazers, which was inferred to be caused by a reduction in predation pressure.

In general, there was a high degree of uncertainty in the type of response that the different biological components were predicted to exhibit to exploitation pressures. Mussel bed habitat, mussel symbiotrophs, shrimp symbiotrophs, grazers, suspension feeders, detritivores, vent biota reproductive output, and to a lesser degree, non-vent biota, were all predicted to have a high incidence of sign indeterminate (uncertain) responses to exploitation pressures. For biological components that did not exhibit a high degree of uncertainty, there was a high prevalence of predicted zero response to exploitation pressures. POM of photosynthetic origin was predicted to have a zero response to all exploitation pressures. POM of chemosynthetic origin, suspended microorganisms, sulphide microorganisms, warm diffuse flow attached microorganisms, cool diffuse flow attached microorganisms, and exogenous dispersive stages of vent species were all predicted to have a high incidence of zero responses.

Some biological components were predicted to have a higher incidence of negative response across the suite of exploitation pressures. Predators and scavengers were predicted to have the most negative response overall, exhibiting certain negative responses for all exploitation pressures apart from reductions in warm diffuse flow or cold diffuse flow. Non-vent biota were predicted to have three certain negative and four likely negative responses across all exploitation pressures, whilst POM of chemosynthetic origin was predicted to have five certain negative responses. Exogenous dispersive stages of vent species were only predicted to have certain negative responses to pressures related to reduced contributions to external recruitment, such as the effect of habitat removal (P1), the effect of sediment clogging on suspension-feeding structures and inhibition of oxygen respiratory structures (P6) and plume toxicity (P8). Sulphide microorganisms were only predicted to have certain negative responses to a reduction in the subsurface connectivity of fluid flow within the hydrothermal vent field and plume toxicity. Mussel bed habitat, mussel symbiotrophs, and suspension feeders were predicted to have likely negative responses to reduced subsurface connectivity. Vent biota reproductive output was predicted to have a certain negative response to reduced subsurface connectivity and a likely negative response to plume toxicity.

The only biological components that were predicted to have positive responses to any exploitation pressures were warm diffuse flow attached microorganisms, cool diffuse flow attached microorganisms, shrimp symbiotrophs, and grazers. Warm diffuse flow attached microorganisms and symbiotrophic shrimp were predicted to have certain positive and likely positive responses respectively to a reduction in cool diffuse flow, as the pressure scenario included an equal and opposite increase in warm diffuse flow. Similarly, cool diffuse flow microorganisms were predicted to have a certain positive response to a reduction in warm diffuse flow due to an equal and opposite increase in cool diffuse flow, which is the preferred hydrothermal environment for this group. Grazers were predicted to have a likely positive response to a reduction in exogenous POM of chemosynthetic origin (P2), and to a reduction in subsurface connectivity; these positive responses were inferred to reflect a potential reduction in predation pressure on this group resulting from the web of interactions in the ecosystem model.

		Habitat removal			Hydrothermal flow			Sediment clogging		Plume toxicity	
		P1	P2	P10	P3	P4	P5	P6	P7	P8	P9
Physical	Vent field subsurface connectivity	⬜	⬜	⬜	🟥	⬜	⬜	⬜	⬜	⬜	⬜
	Focused flow	⬜	⬜	⬜	🟥	⬜	⬜	⬜	⬜	⬜	⬜
	Warm diffuse flow	⬜	⬜	⬜	🟥	🟥	🟦	⬜	⬜	⬜	⬜
	Black smoker plumes	⬜	⬜	⬜	🟥	⬜	⬜	⬜	⬜	⬜	⬜
	Cool diffuse flow	⬜	⬜	⬜	🟥	🟦	🟥	⬜	⬜	⬜	⬜
Biological	Particulate organic matter photosynthetic	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
	Particulate organic matter chemosynthetic	🟥	🟥	⬜	🟥	🟨	🟨	⬜	⬜	⬜	🟥
	Suspended microorganisms	⬜	⬜	⬜	🟥	🟨	🟨	⬜	⬜	⬜	⬜
	Sulphide microorganisms	⬜	⬜	⬜	🟥	🟨	🟨	⬜	⬜	⬜	🟥
	Warm diffuse flow attached microorganisms	⬜	⬜	⬜	🟥	🟥	🟦	⬜	⬜	⬜	🟥
	Cool diffuse flow attached microorganisms	⬜	⬜	⬜	🟥	🟦	🟥	⬜	⬜	⬜	🟥
	Mussel bed habitat	🟨	🟨	⬜	🟧	🟨	🟨	🟨	🟨	🟨	🟨
	Mussel symbiotrophs	🟨	🟨	⬜	🟧	🟨	🟨	🟨	🟨	🟨	🟨
	Shrimp symbiotrophs	🟨	🟨	⬜	🟨	🟧	🔹	🟨	🟨	🟨	🟨
	Grazers	🟨	🔹	⬜	🔹	🟨	🟨	🟨	🟨	🟨	🟨
	Suspension feeders	🟨	🟨	⬜	🟧	🟨	🟨	🟨	🟨	🟨	🟨
	Detritivores	🟨	🟨	⬜	🟧	🟨	🟨	🟨	🟨	🟨	🟧
	Predators and scavengers	🟥	🟥	⬜	🟥	🟨	🟨	🟥	🟥	🟥	🟥
	Vent biota reproductive output	🟨	🟨	⬜	🟥	🟨	🟨	🟨	🟨	🟨	🟧
	Exogenous dispersive stages of vent species	🟥	⬜	⬜	⬜	⬜	⬜	🟥	⬜	🟥	⬜
	Non-vent biota	🟧	🟧	🟥	🟥	🟨	🟨	🟨	🟧	🟨	🟥

Pressure category	Abbreviation	Pressure description
Habitat removal	P1	Effect of habitat removal on exogenous dispersive stages of vent species (recruitment)
	P2	Effect of habitat removal on exogenous particulate organic matter of chemosynthetic origin (POMc)
	P10	Effect of habitat removal on non-vent biota
Hydrothermal flow	P3	Changes to hydrothermal flow reduces subsurface fluid connectivity of the vent field
	P4	Changes to hydrothermal flow reduces warm diffuse flow
	P5	Changes to hydrothermal flow reduces cool diffuse flow
Sediment clogging	P6	Effect of sediment clogging on exogenous dispersive stages of vent species (recruitment)
	P7	Effect of sediment clogging on adult vent and non-vent biota
Plume toxicity	P8	Effect of plume toxicity on exogenous dispersive stages of vent species (recruitment)
	P9	Effect of plume toxicity on adult vent and non-vent biota

Figure 4. Qualitative response predictions of hydrothermal vent ecosystem model components (rows) to each of ten pressure effects (columns) detailed in Tables 3 – 5. Model based on signed digraph of Figure 2, but without dashed-line links or variables associated with adjacent vent field.

Cumulative impact multiple pressures

The nine perturbation scenarios detailed in Table 6 were used to predict the cumulative impact of multiple pressures resulting on the hydrothermal vent ecosystem from exploitation activities at PMS deposits (Figure 5). The response of physical components, including vent field subsurface connectivity, focused flow, warm diffuse flow, black smoker plumes, and cool diffuse flow, was scenario-specific, depending on the nature of hydrothermal fluid flow modification that the scenario entailed. In general, most biological components of the system were predicted to have a negative response to the modelled perturbation scenarios (i.e., decreased abundance and biomass).

Two of the biological components were predicted to have a certain negative response across all exploitation scenarios (exogenous dispersive stages of vent species, non-vent biota) and three biological components were predicted to have a mix of certain negative and likely negative responses (POM of chemosynthetic origin, predators and scavengers, and vent biota reproductive output). Only POM of photosynthetic origin was predicted to have a zero response (no response) to all exploitation scenarios. Grazers were predicted to have likely positive responses to four exploitation scenarios and was the only biological component predicted to have a likely positive response to any exploitation scenario. Warm diffuse flow attached microorganisms and cool diffuse flow attached microorganisms were predicted to have certain negative response to six scenarios, sign indeterminate (uncertain) responses to two scenarios and zero responses to one scenario. Suspended microorganisms were predicted to have certain negative responses to two scenarios, sign indeterminate responses to four scenarios and zero responses to three scenarios. Detritivores were predicted to have likely negative responses to four scenarios and sign indeterminate responses to five scenarios. For mussel bed habitat, mussel symbiotrophs, and suspension feeders, each was predicted to have a likely negative response to two scenarios with sign indeterminate response for seven scenarios indicating a high degree of uncertainty in the predicted response of these ecosystem components.

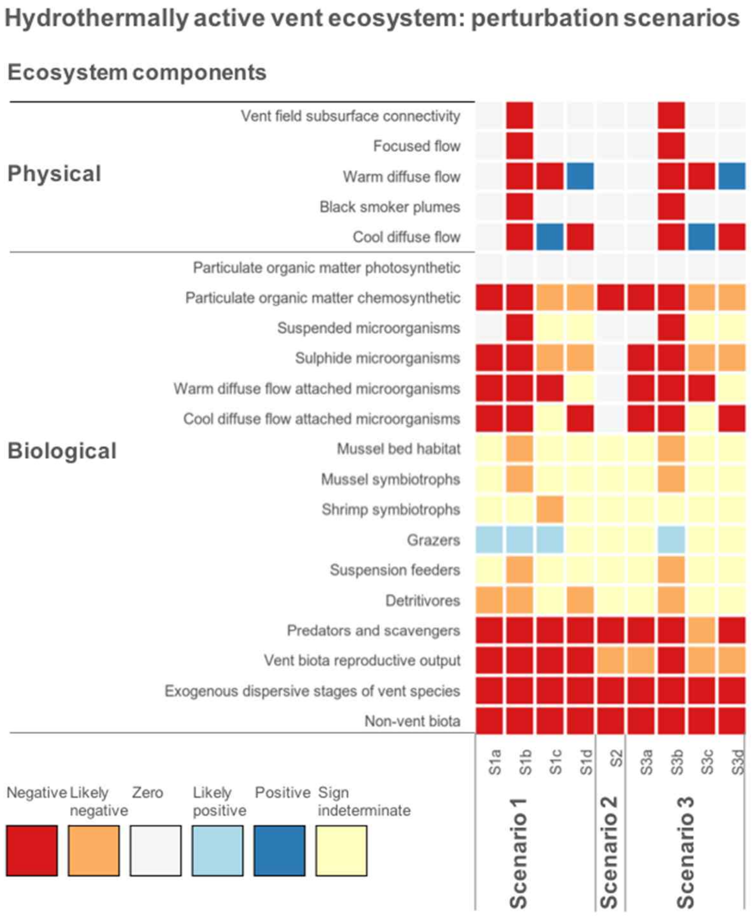
The two perturbation scenarios that were predicted to be the most negative overall for the greatest number of ecosystem components were where exploitation activity reduced subsurface connectivity within the vent field. The ecosystem components in the model were predicted to have the same response to this reduction in subsurface connectivity, irrespective of whether it was a hydrothermally active (Scenario 1b) or a hydrothermally inactive (Scenario 3b) PMS deposit that was mined. For the two scenarios where exploitation activity reduced subsurface connectivity, two thirds of the ecosystem components were predicted to have a certain negative response (14 out of 21). These included all physical environment components (vent field subsurface connectivity, focused flow, warm diffuse flow, black smoker plumes, and cool diffuse flow) and many of the biological components in the model (POM of chemosynthetic origin, suspended microorganisms, sulphide microorganisms, warm diffuse flow attached microorganisms, cool diffuse flow attached microorganisms, predators and scavengers, vent biota reproductive output, exogenous dispersive stages of vent species, and non-vent biota). Most of the remaining biological components were predicted to have a likely negative response to these two scenarios (4 out of 21: mussel bed habitat, mussel symbiotrophs, suspension feeders, and detritivores), with shrimp symbiotrophs predicted to have a sign indeterminate response, and grazers predicted to have a likely positive response. Only POM of photosynthetic origin was predicted to have a zero response to Scenario 1b and Scenario 3b.

The scenario that was predicted to be the least negative overall for the most ecosystem components at the unmined hydrothermally active habitat was where exploitation occurred at a hydrothermally active PMS deposit in a different vent field (Scenario 2). In this scenario, less than one fifth of ecosystem components were predicted to have a certain negative response (4 out of 21: POM of chemosynthetic origin, predators and scavengers, exogenous dispersive stages of vent species, and non-vent biota) and only one component was predicted to have a likely negative response (vent biota reproductive output). The rest of the biological components were predicted to have either zero responses (5 out of 21: POM of photosynthetic origin, suspended microorganisms, sulphide microorganisms, warm diffuse flow attached microorganisms, and cool diffuse flow attached microorganisms) or sign indeterminate responses (6 out of 21: mussel bed habitat, mussel symbiotrophs, shrimp symbiotrophs, grazers, suspension feeders, and detritivores). All of the physical components in the model were predicted to have zero responses to Scenario 2 because there was no subsurface connectivity between the exploited active PMS deposit and the observed unmined hydrothermal vent habitat.

The two perturbation scenarios where exploitation activities did not disturb subsurface hydrothermal connectivity within the vent field were more negative overall than where exploitation occurred in a different vent field, but less negative than where exploitation activities reduced subsurface connectivity. The response of ecosystem components where exploitation activities did not disturb subsurface hydrothermal connectivity within the vent field was very similar, regardless of whether exploitation occurred at a hydrothermally active (Scenario 1a) or inactive (Scenario 3a) PMS deposit within the same vent field. In both scenarios, a large proportion of biological ecosystem components were predicted to have certain negative responses (7 or 8 out of 21). The same ecosystem components were predicted to have certain negative responses (POM of chemosynthetic origin, sulphide microorganisms, warm diffuse flow attached microorganisms, cool diffuse microorganisms, predators and scavengers, exogenous dispersive stages of vent species, and non-vent biota) in both Scenario 1a and Scenario 3a, except for vent biota reproductive output, which was predicted to have a certain negative response in Scenario 1a but a likely negative response in Scenario 3a. The same biological components were predicted to have sign indeterminate responses (mussel bed habitat, mussel symbiotrophs, shrimp symbiotrophs, and suspension feeders) to Scenario 1a and Scenario 3a, except for detritivores, which were predicted to have a sign indeterminate response in Scenario 3a but a likely negative response in Scenario 1a, and grazers, which were predicted to have a sign indeterminate response in Scenario 3a but a likely positive response in Scenario 1a. POM of photosynthetic origin and suspended microorganisms were the only biological components predicted to have a zero response to Scenario 1a and Scenario 3a. All of the physical components of the model were predicted to have zero responses to Scenario 1a and Scenario 3a because the subsurface fluid flow connection between the hydrothermally inactive PMS deposit and the rest of the vent field was not disturbed.

The four perturbation scenarios where exploitation activities either reduced warm diffuse flow or cool diffuse flow to the unmined hydrothermally active habitat were predicted to elicit a similar number of negative responses from ecosystem components. Where exploitation of a hydrothermally inactive PMS deposit in the same vent field resulted in reduced warm diffuse flow (Scenario 3c) or reduced cool diffuse flow (Scenario 3d), this was predicted to elicit the fewest certain negative responses (4 and 5 out of 21 respectively). Exploitation of a hydrothermally active PMS deposit in the same vent field was predicted to elicit the same number of certain negative responses (6 out of 21), irrespective of whether this reduced warm diffuse flow (Scenario 1c) or cool diffuse flow (Scenario 1d). Exogenous dispersive stages of vent species and non-vent biota were predicted to have certain negative responses to all four scenarios where either warm or cool diffuse flow was reduced. Predators and scavengers were predicted to have certain negative responses in three out of the four scenarios, with a likely negative response predicted for where exploitation of an inactive PMS deposit reduced warm diffuse flow. Vent biota reproductive output was predicted to have a certain negative response to both scenarios where a hydrothermally active PMS deposit was exploited but a likely negative response to scenarios where a hydrothermally inactive PMS deposit was exploited. POM of chemosynthetic origin and sulphide microorganisms were predicted to have likely negative responses in all four of the scenarios where warm or cool diffuse flow was reduced.

For some ecosystem components, the predicted response had a clear link to whether exploitation activities reduced warm or cool diffuse flow. Where exploitation activities at either a hydrothermally active or inactive PMS deposit reduced warm diffuse flow, warm diffuse flow attached microorganisms were predicted to have a certain negative response, and cool diffuse flow attached microorganisms were predicted to have a sign indeterminate response. Where exploitation activities at either a hydrothermally active or inactive PMS deposit reduced cool diffuse flow the opposite responses were predicted to occur. For other ecosystem components, the predicted response to a reduction in warm or cool diffuse flow was less certain. Shrimp symbiotrophs were predicted to have a likely negative response to where exploitation of an active PMS deposit reduced warm diffuse flow but a sign indeterminate response to where exploitation of an inactive PMS deposit reduced warm diffuse flow or exploitation of an active or inactive PMS deposit reduced cool diffuse flow. Detritivores were also predicted to have sign indeterminate responses to where exploitation of an inactive PMS deposit reduced warm or cool diffuse flow, in addition to where exploitation of an active PMS deposit reduced warm diffuse flow, but a likely negative response to where exploitation of an active PMS reduced cool diffuse flow. Grazers were predicted to have a likely positive response to where exploitation of an active PMS deposit reduced warm diffuse flow, but a sign indeterminate response to the other three exploitation scenarios that reduced warm or diffuse flow. Suspended microorganisms, mussel bed habitat, mussel symbiotrophs and suspension feeders were predicted to have sign indeterminate responses to scenarios where warm or cool diffuse flow was reduced. POM of photosynthetic origin was the only biological component predicted to have a zero response to all exploitation scenarios where warm or cool diffuse flow was reduced.



Abbreviation	Perturbation scenario description	Pressure combinations
Scenario 1 – Hydrothermally active PMS deposit exploited within the same vent field		
S1a	No impact on subsurface fluid connectivity	P1, P2, P6 – 9
S1b	Reduced subsurface fluid connectivity	P1, P2, P3, P6 – P9
S1c	Reduced warm diffuse flow	P1, P2, P4, P6 – P9
S1d	Reduced cool diffuse flow	P1, P2, P5, P6 – P9
Scenario 2 – Hydrothermally active PMS deposit exploited in a different vent field		
S2	No existing subsurface fluid connectivity	P1, P2, P6, P8
Scenario 3 – Hydrothermally inactive PMS deposit exploited within the same vent field		
S3a	No impact on subsurface fluid connectivity	P6 – P9, P10
S3b	Reduced subsurface fluid connectivity	P3, P6 – P9, P10
S3c	Reduced warm diffuse flow	P4, P6 – P9, P10
S3d	Reduced cool diffuse flow	P5, P6 – P9, P10

Figure 5. Qualitative response predictions of cumulative impacts to hydrothermal vent ecosystem model components (rows) for nine perturbation scenarios (columns) detailed in Table 6. Model based on signed digraph of Figure 2, but without dashed-line links or variables associated with adjacent vent field.

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