DPSIR Components and Candidate Indicators for Polymetallic Nodule Mining within the NORI-D Lease of the Clarion-Clipperton Zone

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

June 2025

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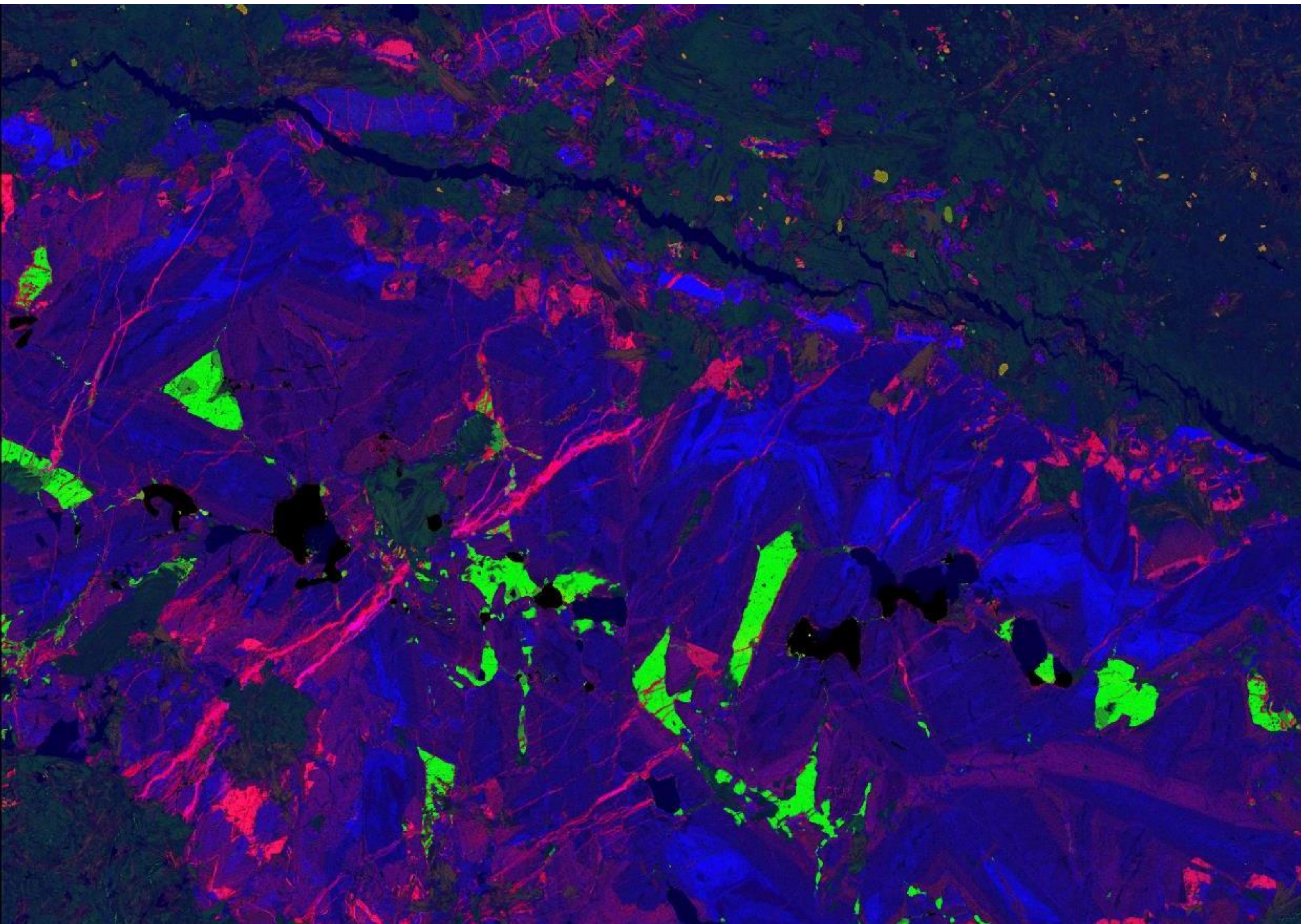

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Acknowledgement of Country

Acknowledgements

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1 Introduction

This report summarises the development of candidate indicators for the monitoring and management of proposed deep-sea mining of polymetallic nodules within the NORI-D lease of the Clarion-Clipperton Zone (CCZ), Pacific Ocean. The development of candidate indicators is based on an understanding of how ecosystem components and processes can be affected by nodule collection activities operating in both pelagic and benthic environments. Indicators are identified according to the Driver-Pressure-State-Impact-Response (DPSIR) framework (Carr *et al*. 2007, Langmead *et al*. 2007, Niemeijer and De Groot 2008) to understand how deep-sea mining activities lead to pressures that affect the state of marine ecosystems and impact associated values and services, and to evaluate the effectiveness of management responses.

A central requirement of this framework is that the cause-effect relationship, identified between a pressure and change in ecosystem state, is clearly identified; for complex ecosystems this requires the use of mathematical process-based models that address direct and indirect effects, and system feedback (Hayes *et al*. 2015). Here we make us of qualitative mathematical models (Puccia and Levins 1985, Dambacher *et al*. 2009) to describe the pelagic and benthic ecosystems in the CCZ and identify candidate ecological indicators relevant to proposed nodule mining activities in the NORI-D lease. In this approach, candidate indicators are those indicators that have a predictable response to a given pressure on the system, thus allowing for a causal interpretation that informs management responses.

2 Methods

2.1 Selection of experts for qualitative modelling workshops

Qualitative mathematical models were constructed through expert elicitation in workshops attended by biologists with knowledge relevant to the pelagic and benthic ecosystems of concern. Potential workshop participants were identified through Boolean searches in the Web of Science Core Collection without filters (https://www.webofscience.com/wos/woscc/basic-search) of peer-reviewed literature conducted on 23 August 2022. Five categories of search terms (Table 1) were variously combined (Table 2) to identify sets of published papers that contained at least one search term in each category.

Boolean searches that included “Clarion” were deemed too restricted in the number of papers identified. Boolean search included authors that appeared in both search G (which included terms for “System”, and search H, which included terms for “Disturb”, giving a total of 12,671 authors that occurred in both searches. Experts for the workshop were selected based on these publication records using the procedure described in Hosack *et al*. (2023, Appendix A) was implemented with the following criteria: a) publication records were subset to journal articles published between the years 2000 and 2022; b) authors were then ranked according to the average of their H-index scores, independently derived from searches G and H and normalised between zero and one for each search, to identify authors with strong publication records in deep-sea ecosystems with an emphasis on both system processes and disturbance.

Table 1. Categories of search terms used to identify publications in deep-sea science with * as a wildcard operator.

Clarion	Deep	Life	System	Disturb
Clarion Clipperton	deep sea	bacteria*	biogeochem*	assess*
	abys*	benth*	carbon	disturbance
		fauna	communit*	impact
		fish	cycl*	mining
		foram*	*diversity	noise
		life	ecolog*	plume
		microb*	ecosystem	predict*
		nodule	function*	probabilit*
		pelagi	habitat	quanti*
		vertebrate	model*	recoloniz*
			nutrient	recovery
			sediment*	risk
			service	sedimentation
				vulnerab*

Table 2. Boolean searches based on combinations of terms in five categories (Table 1) that were used to identify publications and authors of deep-sea biology. Searches were constructed with an OR operator for within-category combinations and with an AND operator for between-category combinations. In I, publications derived from searches G and H were combined to compile a list of 12,671 authors that occurred in both searches.

Boolean search		Publications	Authors
(A)	**Clarion**	350	Not compiled
(B)	**Deep**	45,250	Not compiled
(C)	**Deep-AND-Clarion**	267	Not compiled
(D)	**Deep-AND-Life**	18,712	Not compiled
(E)	**Deep-AND-System**	28,929	Not compiled
(F)	**Deep-AND-Disturb**	13,488	Not compiled
(G)	**Deep-AND-Life-AND-System**	14,842	23,931
(H)	**Deep-AND-Life-AND-Disturb**	6,403	13,549
(I)	**Deep-AND-Life-AND-System & Deep-AND-Life-AND-Disturb**	14,842 & 6,403	12,671

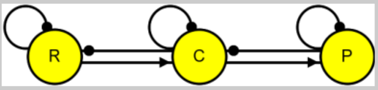
Drawing on the list of authors identified in search I, the publication record of the top 170 scientists was examined to identify and omit those with research interests outside the intended ecosystem-level focus of the workshop (19; *i.e.*, genomics, paleobiology), those focused on research of hydrothermal vents (7), those deceased (2), or those connected with the CSIRO research consortium or its institutions (5), which consequently excluded 33, leaving a list totalling 137. The geographic spread of these 137 scientists included East Asia, North America and Europe, and it was decided that two separate workshops would be convened to limit travel distance of participants, one in London, 24-26 January 2023, and a second in Long Beach, California, 31 January to 2 February 2023. Email invitations were sent to the top 40 scientists residing in Europe and the top 40 in North America and East Asia. Of these 80 invitations, 25 were accepted; after six withdrawals due to scheduling conflicts, nine experts attended the London workshop and ten attended the Long Beach workshop.

2.2 Model elicitation

During the elicitation workshops, experts were asked to describe the physical and ecological processes involved in the pelagic and benthic ecosystems of the NORI-D area. An emphasis was placed on defining model components in terms of their ecological function and not strictly by taxonomic or sized-based definitions. Descriptions of the system were translated into signed directed graphs or signed digraphs (Box 1), where model links represent the sign (+, -, 0) of direct effects transmitted between model components or variables.

Box 1. Qualitative mathematical models and their analysis

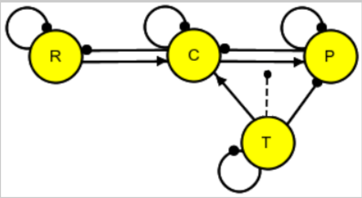
Qualitative mathematical modelling proceeds from the construction and analysis of signed directed graphs, or signed digraphs, which are depictions of the variables and interactions of a system. Here we are only concerned with the sign (*i.e.*, positive, negative, zero) of the direct effects that link the variables. The below signed digraph is a straight-chain system with a basal resource (R), consumer (C) and predator (P). There are two predator-prey type relationships, where the predator or consumer 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.



Stability.—Based only on this qualitative structure, it can be determined that this model is stable (Puccia and Levins 1985, Dambacher *et al.* 2003b), which is a result, in part, of it having only negative feedback cycles. The paths leading from the predators to their prey and back to the predator are negative feedback cycles of length two, and there are no positive (destabilizing) cycles. Thus, if this system were to experience a sudden disturbance it would be expected to return relatively quickly to its previous state or equilibrium.

Pressure response prediction.—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.

Modified interactions.—Links representing *modified interactions* (Dambacher and Ramos-Jiliberto 2007) describe physical or biological variables that can regulate the intensity of the interaction of other variables. For example, a predator's ability to capture its prey can, in aquatic ecosystems, be reduced by water column turbidity, thus turbidity (T) modifies (suppresses) the predator-prey interaction, which is represented below by a dash-lined link. This modified interaction creates additional direct effects in the system, detailed below as negative link from T to P for reduced rate of consumption and birth, and positive link from T to C for reduced rate of predation mortality.



Experts attending the London workshop had domain knowledge centred on benthic species and processes and resulting models focused on a benthic ecosystem and a benthic microbial subsystem (Fig. 1). Experts attending the Long Beach workshop had domain knowledge across both pelagic and benthic biology, and models were developed that described both pelagic and benthic ecosystems (Fig. 2).

(a)

(b)

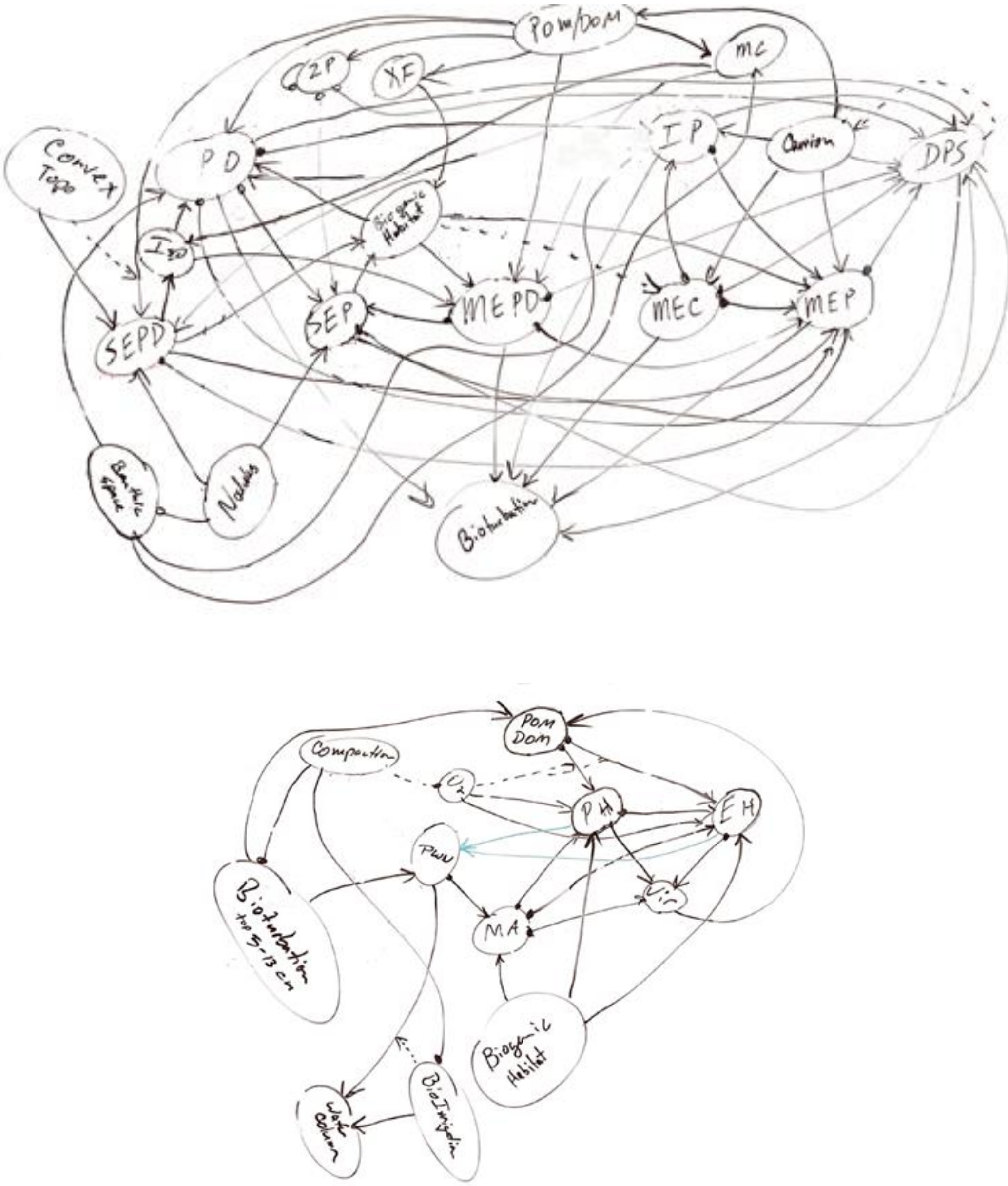


Figure 1. Whiteboard image of signed digraph models from the London expert elicitation workshop. The signed digraph represents ecosystem components (nodes) and processes (edges), including a benthic (a) and benthic microbial ecosystem model (b). Edges represent direct effects, where positive effects end in an arrow and negative effects end in a filled circle; see Appendix Table 4 for variable abbreviations and names.

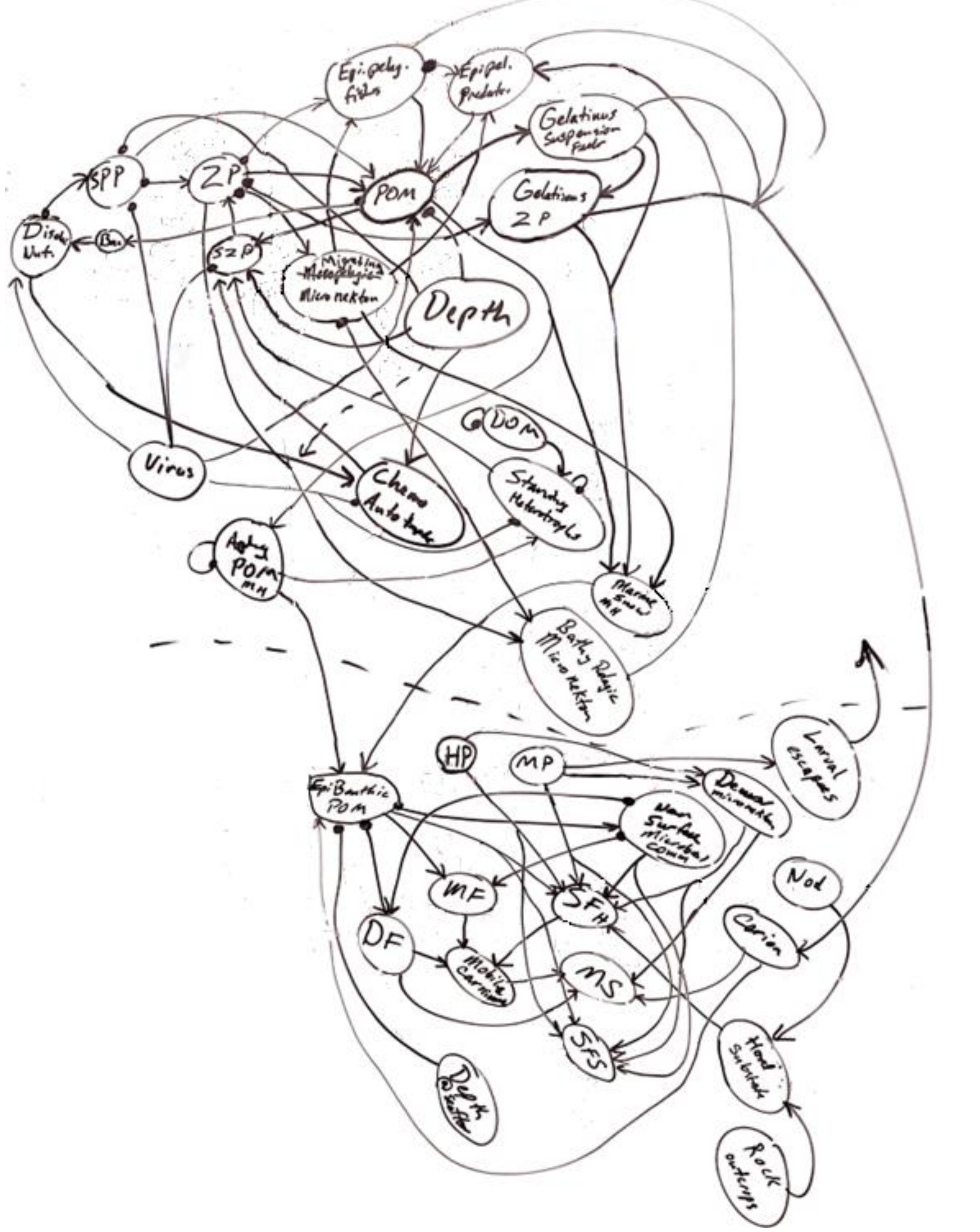


Figure 2. Whiteboard image of signed digraph model from the Long Beach expert elicitation workshop. The signed digraph represents ecosystem components (nodes) and processes (edges), including a pelagic model and benthic model (separated by dashed line). Edges represent direct effects, where positive effects end in an arrow and negative effects end in a filled circle; see Appendix Table 4 for variable abbreviations and names.

After the signed digraph models were constructed, workshop participants then considered how proposed mining activities could possibly create pressures that could impact the modelled ecosystem. Based on a description of proposed mining activities, sets of associated pressures were systematically assessed to identify possible impacts to any of the components or processes detailed in the signed digraph models.

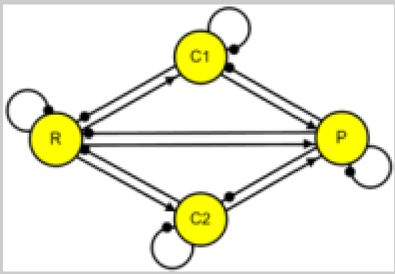
2.3 Model revision, documentation and analysis

Following the two workshops, the models from each workshop were combined into a single representation of the pelagic and benthic ecosystem. The process of combining the models proceeded by identifying equivalencies in the functions and descriptions of system components (Appendix Table 4) and representing ecosystem processes with a commensurate level of resolution across the biological and physical components of the model. The various pressures identified in the two workshops were also combined, with the effects on the ecosystems classified to denote their spatial extent (localised, dispersive, regional), their frequency during operations (one-off, intermittent, continuous), their persistence after operations (transient, persistent, permanent), their potential to accumulate in situ over time (yes, no), and their potential to bio-accumulate in benthic or pelagic organisms (yes, no). The revised ecosystem models and descriptions of model components and links were reviewed by workshop participants. Experts contributed editorial suggestions and references of scientific literature to support the descriptions of ecosystem structure and processes represented by the ecosystem models.

Once the structure of a signed digraph model was defined, it was then analysed to determine 1) the model's potential for qualitative stability, and 2) qualitative predictions for response to pressures (Box 1 and 2; Puccia and Levins 1985, Dambacher *et al.* 2002, 2003a and 2003b).

Box 2. Ambiguous response predictions, sign determinacy and candidate indicators

Compared to the system in Box 1, the signed digraph below is a more complex system with an additional consumer and a predator that feeds on more than one trophic level; this added complexity creates multiple pathways with opposite signs between the predator (P) and resource (R).



Here the predicted response of R due to an input to P is ambiguous, because there are now three paths leading from P to R, two positive (P—●C1—●R, P—●C2—●R) and one negative (P—●R). The abundance of the resource can thus be predicted to either increase or decrease. This ambiguity can be approached in two ways. One is to apply knowledge of the relative strength of the links connecting P to R. If P was only a minor consumer of R then the R would be predicted to increase. Alternatively, if R was the main prey of P, and C1 and C2 amounted to only a minor portion of its diet, then R would be predicted to decrease in abundance.

It is often the case, however, that we lack sufficient knowledge of the strength of the links involved in a response prediction. In these instances we can use a statistical approach developed by Dambacher *et al.* 2003a and Hosack *et al.* 2008 that provides a probability of sign determinacy for response predictions. Through computer simulations, path strengths can be randomly allocated to qualitative models, and the sign determinacy of responses predictions compared to the relative balance of positively and negatively signed paths. If there are an equal number of positively and negatively signed paths between variables, then an increase or decrease in a variable is equally likely. In the above example with two positively signed paths and one negatively signed path, there is a net of one positive path (*i.e.*, it is considered that a negatively signed path cancels a positively signed path) out of a total of three paths. The ratio of the net to the total number of paths in a response prediction has been determined to be a robust means of assigning probability of sign determinacy to response predictions. Based on computer simulations by Dambacher *et al.* 2003a and Hosack *et al.* 2008, R can be expected to increase roughly three out of four times, but also decrease one out of four times; accordingly, one can assign a level of reliability, or ambiguity, to the prediction for a positive response in R.

The problem of identifying useful and informative indicators to monitor change in state of impacted ecosystems is closely aligned with the problem of sign determinacy for qualitative model predictions (Hayes *et al*. 2015). For example, for a pressure having a direct negative effect on the growth rate of variable R, the responses of variables C1 and C2 are qualitatively indeterminate (*i.e.*, there responses are determined by both negatively and positively signed paths), while the response signs of variables R and P are both completely determined and thus informative for any pressure acting on R. Thus, for a perturbation scenario involving an input to R, variables P and R would be identified as candidate indicators for monitoring, while variables C1 and C2 would not.

3 Results

3.1 Revised signed digraph ecosystem model

The revised signed digraph model that was developed from the London and Long Beach workshops includes both pelagic and benthic ecosystem components (Fig. 3). Definitions of the model components (graph nodes) are provided in Appendix Table 5 and description of model interactions (graph edges or links) in Appendix Table 6. Potential pressures from deep-sea mining, other human activities and climate change are provided in Appendix Table 7.

3.2 Pelagic ecosystem

Primary production in the euphotic zone of the pelagic system is dominated by phytoplankton, with their growth strongly determined by light levels and concentrations of nutrients. Below depths of 100 m the dominance of primary production shifts to chemoautotrophs due to light attenuation. Secondary production in epi- and mesopelagic ocean waters is dominated by zooplankton (*e.g.*, copepods and krill) that primarily consume phytoplankton, but also protistan grazers (*e.g.*, Foraminifera, Radiolaria and Cilia). Other groups of secondary producers include starved heterotrophs that rely on dissolved organic matter, and protistan grazers, through their consumption of pelagic chemoautotrophs and starved heterotrophs. Pelagic viruses regulate populations of pelagic bacteria and plankton through viral lysis, with resulting mortality of host cells contributing to stores of water-column nutrients and particulate organic matter.

Populations of zooplankton are the main food resource of gelatinous and nekton predators. Gelatinous predators (*i.e.,* cnidarians) are important consumers of zooplankton at all depths. In the epipelagic zone, surface nekton are represented by predatory fishes and invertebrates. Migrating micronekton (*e.g.,* myctophids, squid and shrimp) feed on zooplankton in the epipelagic zone during the night and move to deeper mesopelagic waters during daylight hours to avoid predation by surface nekton and top predators. Zooplankton populations existing in deep mesopelagic and bathypelagic waters are also prey of deep nekton. Top predators (*i.e.,* sea birds, large fishes, and marine mammals) consume nekton primarily in epipelagic waters, with some taxa being able to extend their foraging range to the mesopelagic zone or even deeper (*e.g.,* sperm whales).

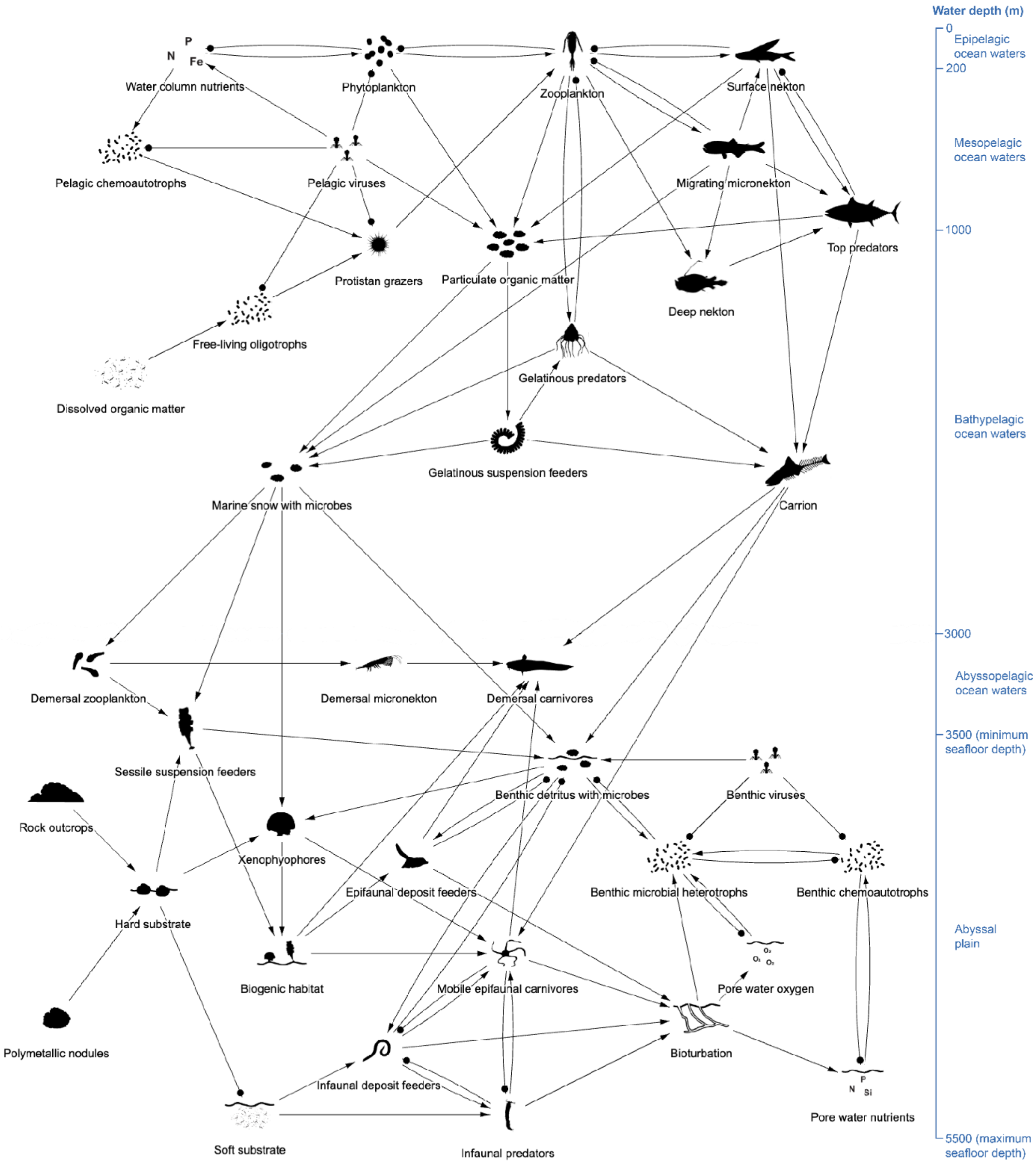


Figure 3. Ecosystem model of pelagic (upper section) and benthic (lower section) ecosystems in the Clarion-Clipperton Zone. Nodes (icons) represent biological, physical and biogeochemical components, organised into functional groups (Appendix Table 5). Edges (links) represent ecosystem processes, defined as either positive (ending in arrow) or negative (ending in filled circle) direct effects between ecosystem components (Appendix Table 6). The International Union for Conservation of Nature (IUCN) Global Ecosystem Typology was used to delineate functional gradients throughout the ocean water column (epipelagic, mesopelagic, bathypelagic and abyssopelagic) down to the deep seafloor (abyssal plain) (Keith *et al.* 2022).

Particulate organic matter is composed of waste products and decomposing, small-bodied, carrion from populations of plankton, nekton and top predators. Viruses infect phytoplankton, pelagic chemoautotrophs, starved heterotrophs, and protistan grazers, and through viral lysis increase the rate of mortality and conversion of these organisms to particulate organic matter. Particulate organic matter is consumed by gelatinous suspension feeders in epi-, meso- and bathypelagic ocean waters. Through both biotic and abiotic processes, organic matter particles form aggregates referred to as ‘marine snow’. Marine snow forms a substrate for rich microbial communities and can aggregate and grow in size through incorporation of additional waste products from nekton, as well as gelatinous predators and suspension feeders. As these aggregations grow in size, they sink faster and increase the export of organic matter to deeper waters. The other major export pathway is through falls of carrion from top predators, nekton, and gelatinous predators and suspension feeders.

3.3 Benthic ecosystem

Marine snow and carrion that reach the seafloor are the main organic matter input and energy source for the benthic ecosystem. Marine snow near the seafloor is consumed by various types of suspension feeders, including demersal zooplankton, sessile suspension feeders, and xenophyophores. Upon settling on the seafloor, surface marine snow is incorporated into stores of epibenthic detritus, which supports an attached microbial community. Carrion reaching the seafloor also contributes to epibenthic detritus and additionally is consumed by demersal and mobile epifaunal carnivores.

The seafloor in the area of interest is composed primarily of soft substrate interspersed by rock outcrops. Polymetallic nodules are embedded in the surface layer of the seafloor sediments. Both rock outcrops and polymetallic nodules provide hard substrate habitat for the attachment of sessile suspension feeders. Sessile suspension feeders and xenophyophores, both through their live bodies or dead remains, also create biogenic habitat that is a key structural feature benefiting demersal carnivores (*i.e.*, via nursery habitat) and mobile epifaunal carnivores and deposit feeders. Populations of demersal zooplankton are consumed by sessile suspension feeders and demersal micronekton and are a primary source of larval propagules that potentially can emigrate from the system. While polymetallic nodules can be a source of habitat for sessile organisms, their presence on the soft substrates can directly limit the amount of habitat that can be occupied by infauna.

Epibenthic detritus is the primary food source for mobile epifaunal and infaunal deposit feeders. Infaunal deposit feeders are prey of infaunal predators, and both are consumed by the larger mobile epifaunal carnivores, which include brittle stars, decapod crustaceans, amphipods and isopods. Demersal carnivores are generalist predators that, in addition to consuming carrion, consume micronekton and mobile epifauna. Epibenthic detritus is also the primary food source for microbial heterotrophs, which extend down into the top layers of seafloor sediments (generally 5-15 cm). Benthic microbial heterotrophs also consume benthic chemoautotrophs and depend on pore water oxygen for respiration. Benthic chemoautotrophs in the top layers of sediments depend on the availability of pore water nutrients to fuel chemosynthesis, with nutrient availability regulated through bioturbation and bioirrigation, which act to replenish stores of inorganic nutrients in the sediments from overlying waters. Bioturbation is a critical ecosystem function provided by infauna and epifauna that also regulates the transport and availability of labile and semi-labile organic matter in subsurface layers of sediments, where it supports communities of microbial heterotrophs. Benthic viruses also play a key regulating function of populations of both microbial heterotrophs and chemoautotrophs through viral lysis and the subsequent release of organic matter back into the sediments.

In general, the pelagic and benthic ecosystems of the CCZ were described as severely food-limited, or oligotrophic. In the pelagic system, nutrient limitation is a key factor that structures the plankton and microbial communities and the flux of labile and semi-labile organic matter to deeper waters is exceptionally low. The benthic ecosystem relies on highly-processed organic matter that settles on the seafloor, which then becomes even more degraded as it is remineralised or incorporated into seafloor sediments. A key aspect of the model’s structure and dynamics is that the downward transfer of organic matter is the primary process that links the pelagic and benthic ecosystems, with no significant mechanisms, fluxes or effects that propagate upwards from abyssal depths.

3.4 Bayes net validation of pelagic ecosystem model

During the Long Beach workshop, there was considerable discussion of shifts in the relative abundance of pelagic ecosystem components as a function of depth (*e.g.*, see graph links and effects attributed to *Depth* in Fig. 2) Here, it was noted that with depth there is a decreasing abundance of phytoplankton abundance (SPP Fig. 2), lower concentrations of particulate organic matter (POM Fig. 2) and an increase in populations of pelagic chemoautotrophs and protistan grazers (SZp and Chemo Autotrophs Fig. 2). Rather than explicitly including *Depth* as a model variable, we instead represented these dynamics implicitly through the structure of the signed digraph and considered that the growth rate of phytoplankton is diminished through light attenuation as a function of depth. In this way, the loss of light with depth can be interpreted as a negative input to the growth rate of phytoplankton. We made use of these dynamics to perform a validation test of the pelagic ecosystem model through a Bayes net (Hosack *et al*. 2008) that compared the model's qualitative predictions for change due to an input or perturbation to the system with known dynamics or observed shifts in abundance. In Fig. 4, a negative input to phytoplankton, which represents light attenuation with increased depth, is matched with observations of a decrease in phytoplankton abundance and particulate organic matter and an increase in the abundance of protistan grazers and pelagic chemoautotrophs. In this comparison the pelagic ecosystem model was found to have a likelihood of 96.4% when compared to a null model. Thus, the qualitative dynamics of the signed digraph model appears, at least in this limited test, to be highly consistent with some of the known dynamics of the pelagic ecosystem it is intended to represent.

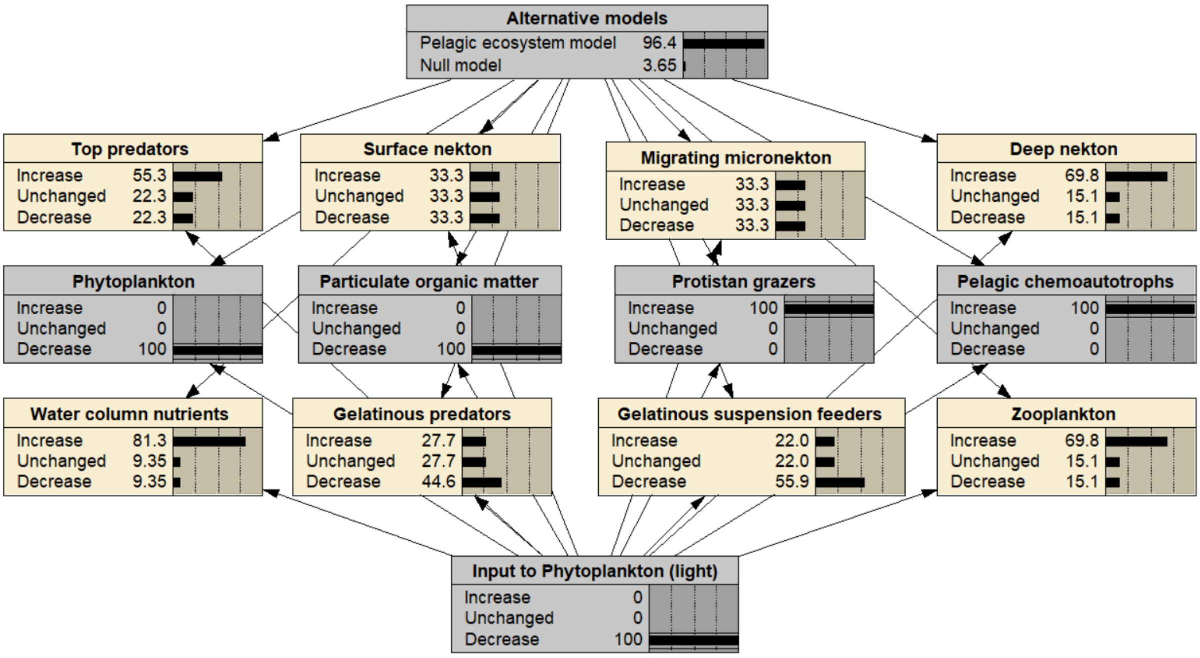


Figure 4. Bayes net validation (Hosack *et al*. 2008) of pelagic ecosystem model (Fig. 3) through a negative input to phytoplankton with observations of decrease in phytoplankton and particulate organic matter and increase in protistan grazers and pelagic chemoautotrophs; NB: dissolved organic matter, pelagic viruses, carrion and marine snow with microbes were omitted from this analysis as they do not contribute to, or receive, feedback or effects from this input scenario.

3.5 Pressure scenarios and response predictions

To assess how the pelagic and benthic ecosystems could be impacted by potential mining activities, a scenario was developed that addressed a worst case where all possible pressures could act on the system, with little or no avoidance or mitigation measures. We also evaluated a set of scenarios for Project Zero that includes the outcomes of mitigation measures which The Metals Company asserts can limit the impacts of mining activities.

In the workshops, a total of eight activities associated with mining operations were identified that could possibly lead to, or produce, pressures that had effects on specific components of the ecosystem model (Appendix Table 7); these include: 1) surface support vessel, 2) midwater sediment plume, 3) return water discharge, 4) riser system, 5) collector vehicle sediment plume, 6) sediment plume deposition, 7) nodule collection and 8) collector vehicle. Additional pressures were identified that were associated with climate change and non-mining related activities (*i.e.*, fish catch, shipping noise and plastic pollution).

The predicted qualitative response of ecosystem components and variables to the pressures was assessed through a series of analyses that included each pressure individually or combined in several scenarios. Response predictions were categorized to represent those that were completely sign-determined (100%; *i.e*., increase or decrease), those with a moderate level of sign determinacy (>80 to <100%; *i.e.*, likely increase or likely decrease), those that were indeterminate (<80%), and those with 100% probability of zero response (*i.e.*, no change).

3.5.1 Worst-case scenarios

In worst-case scenarios, all possible pressures identified by experts in the workshops (Appendix Table 7) were assessed individually, in combinations according to source activities, and in combination with non-mining sources of pressures for the pelagic (Fig. 5) and benthic (Fig. 6) ecosystems.

Examination of the predicted responses to the individual pressures in the pelagic ecosystem (Fig. 5) shows a large proportion to be indeterminate, with completely sign determined responses occurring only for pressure P3c which considers the impact of organic matter in the discharge plume. For all pressures there are a considerable number of ecosystem components with predictions that have at least a moderate level of sign determinacy, providing ample opportunity to assess responses of individual pressures. The same is true for predictions associated with multiple pressures combined in the mining activities.

Compared to predictions from the individual pressures, there is a greater degree of sign determinacy for response predictions within the five perturbation scenarios of Fig. 5. However, the directions of the determined responses are mostly the same for any given component across scenarios, which makes it difficult to discern between them. For instance, across all five scenarios, surface nekton are predicted to increase and gelatinous suspension feeders and gelatinous predators are predicted to decrease. Exceptions are provided by 1) protistan grazers and free-living oligotrophs, which are predicted to decrease with climate change alone, but to increase in three scenarios (S3-S5) that include pelagic mining pressures, and 2) pelagic viruses, which present the opposite pattern and are predicted to increase with climate change and decrease under mining scenarios S4 and S5.

Considering pressure scenario S5, which includes the effects of the midwater sediment plume and return water discharge, there are 13 ecosystem components with sign-determined response predictions that have either positive (zooplankton, protistan grazers, surface nekton, free-living oligotrophs and pelagic chemoautotrophs) or negative (gelatinous suspension feeders, gelatinous predators, migrating micronekton, deep nekton, top predators, marine snow with microbes, carrion and pelagic viruses) signs.

In general, there is a greater degree of sign determinacy in response predictions for the benthic ecosystem model (Fig. 6) than there is in the pelagic ecosystem model (Fig. 5). Predictions associated with multiple pressures combined in mining activities are also determined to a greater degree.

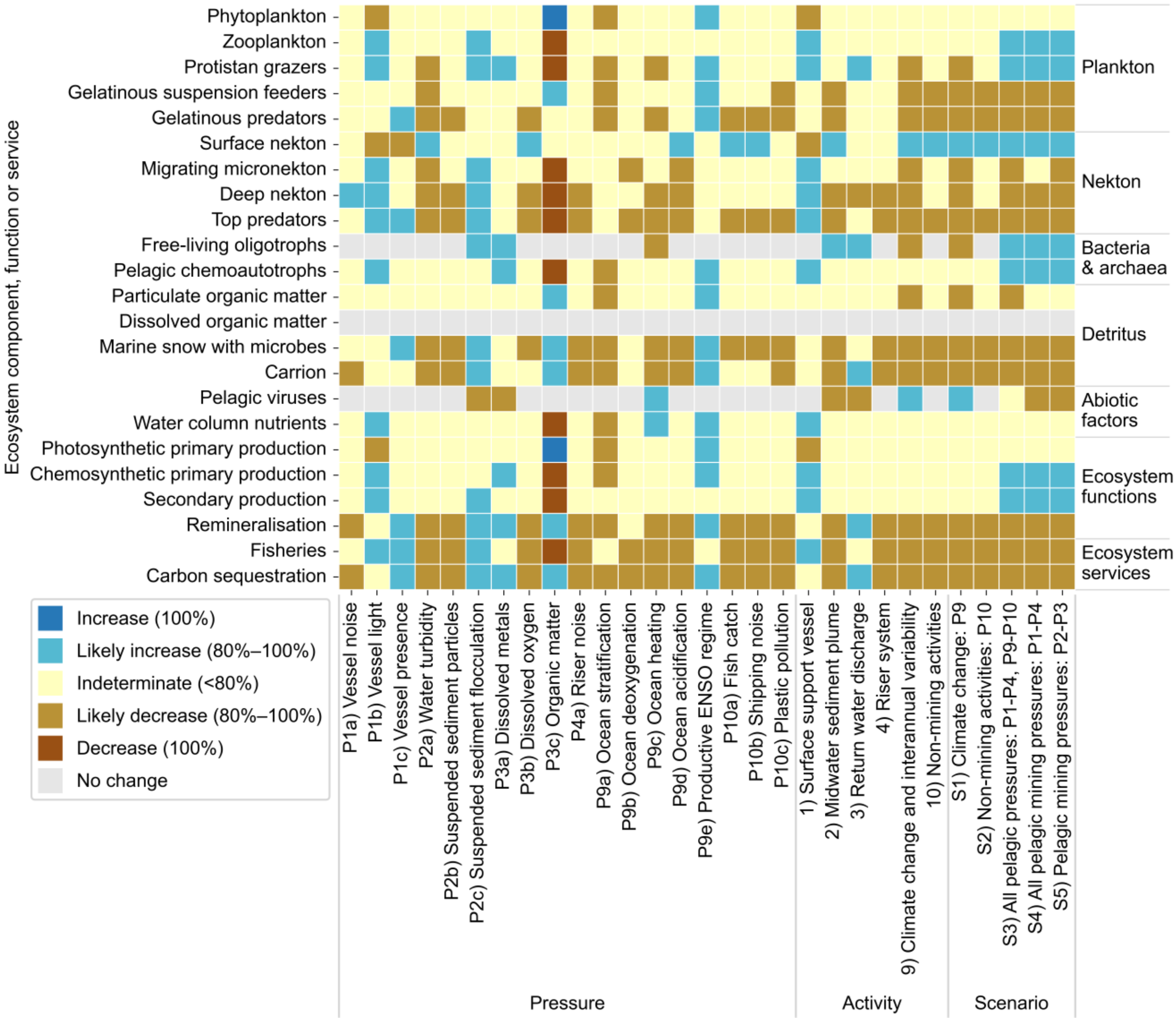


Figure 5. Qualitative predictions of change for components of the pelagic ecosystem model (Fig. 3) in worst-case scenarios that include all mining and non-mining related activities and pressures as detailed in Appendix Table 7.

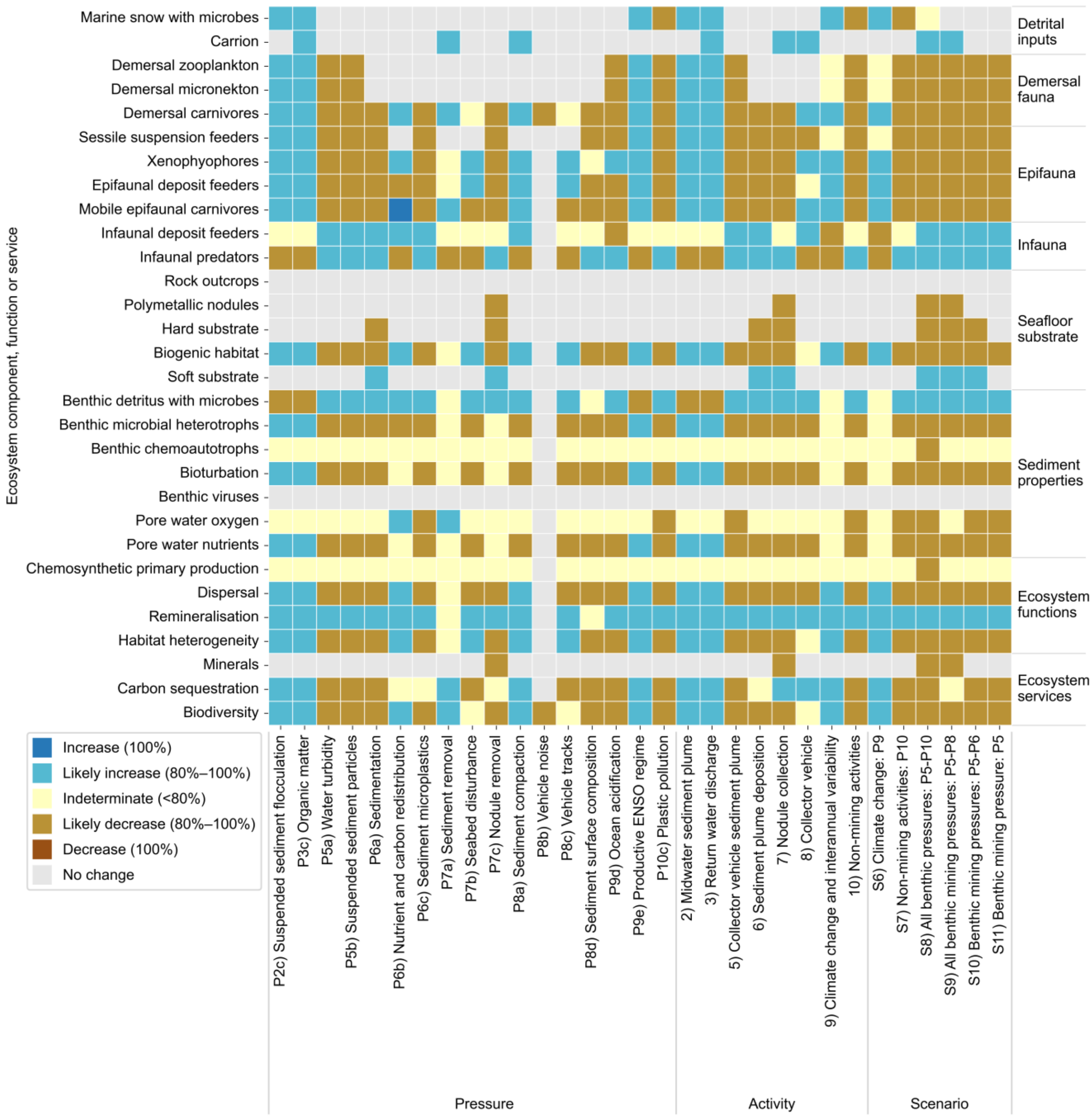


Figure 6. Qualitative predictions of change for components of the benthic ecosystem model (Fig. 3) in worst-case scenarios that include all mining and non-mining related activities and pressures as detailed in Appendix Table 7; NB: includes pressures that originate from pelagic mining activities that directly impact marine snow with microbes or carrion (*i.e.*, P2c and P3c).

Pelagic pressures associated with mining activities that impact the delivery of particulate organic matter and marine snow to the benthic ecosystem (midwater sediment plume P2c and midwater discharge P3c) are generally predicted to have a positive influence on most of the biotic components of the benthic ecosystem, except for negative response predictions for infaunal predators and benthic detritus with microbes. The mechanism by which this increase in benthic productivity is an increased delivery of particulate organic matter to the sea floor due to flocculation of plume-delivered sediments. Predictions combined in the analysis of activities that arise from benthic mining operations (mining activities 5-8), are generally predicted to have a negative influence on most components of the benthic ecosystem model. Notable exceptions include a predicted increase in carrion, infaunal deposit feeders, infaunal predators and benthic detritus with microbes.

Impacts from the scenarios of climate change, non-mining activities and all benthic pressures are negative for most biotic components of the benthic ecosystem model, except for predicted increases in some scenarios for infaunal deposit feeders, infaunal predators and benthic detritus with microbes, and xenophyophores.

Scenarios S9–S11 are intended to assess impacts in areas directly under the collector vehicle (S9), areas adjacent or nearby the mined area (S10) and areas further away (S11). Predictions for biotic component in all three of these scenarios are generally the same, with negative response predictions for most biotic components, while infaunal deposit feeders, infaunal predators and benthic detritus with microbes were predicted to increase. The only differences were for impacts to hard substrate and biogenic habitat, which had predictions for no change in scenarios mimicking increased distance from the collector vehicle.

3.5.2 Project Zero scenarios

For Project Zero scenarios, pressures were limited to a subset of those in Table 7 to meet the needs of The Metals Company in preparing their EIS for Project Zero. Here, The Metals Company asserted that for some activities and pressures (*i.e.,* italicised in Table 7), measurable or significant impacts to pelagic and benthic ecosystems are either highly unlikely due to their spatial extent being extremely limited in comparison to the scale of the lease and region, or that they can be effectively reduced by avoidance and mitigation measures. Project Zero pressures were assessed individually, in combination according to source activities, and in combination with non-mining sources of pressures to address potential impacts at the regional (i.e., outside the NORI-D lease) and lease scale for both the pelagic (Fig. 7) and benthic (Fig. 8) ecosystems.

In assessing potential impacts to pelagic ecosystems for Project Zero, it was asserted by TMC that only the effects from vessel noise, light and presence, effects from suspended sediment particles from the midwater plum, and effects of noise from the riser system were relevant. Moreover, given the two-year time span of project zero, the only relevant non-mining related pressure would be changes in productivity arising from ENSO (Table 7). Pressures relevant to the pelagic ecosystem were the same for both region- and lease-level scenarios (Fig. 7). Mining pressures were predicted to have a positive effect on zooplankton and negative or ambiguous effect on the other components of the system, with positive or negative ENSO's changing only a few of the response predictions.

In assessing the potential impacts to the benthic ecosystems, pressures relevant to Project Zero included the effects of suspended sediment from the collector vehicle plume, plume deposition, nodule removal and collector vehicle tracks (Table 7). Regional- and lease-level scenarios had similar response predictions (Fig. 8), with predictions for increase in infauna and benthic detritus with microbes across most of the scenarios and negative or ambiguous changes for the other components of the system. The inclusion of positive/negative ENSO's did not appear to change the sign of response predictions, except for marine snow with microbes.

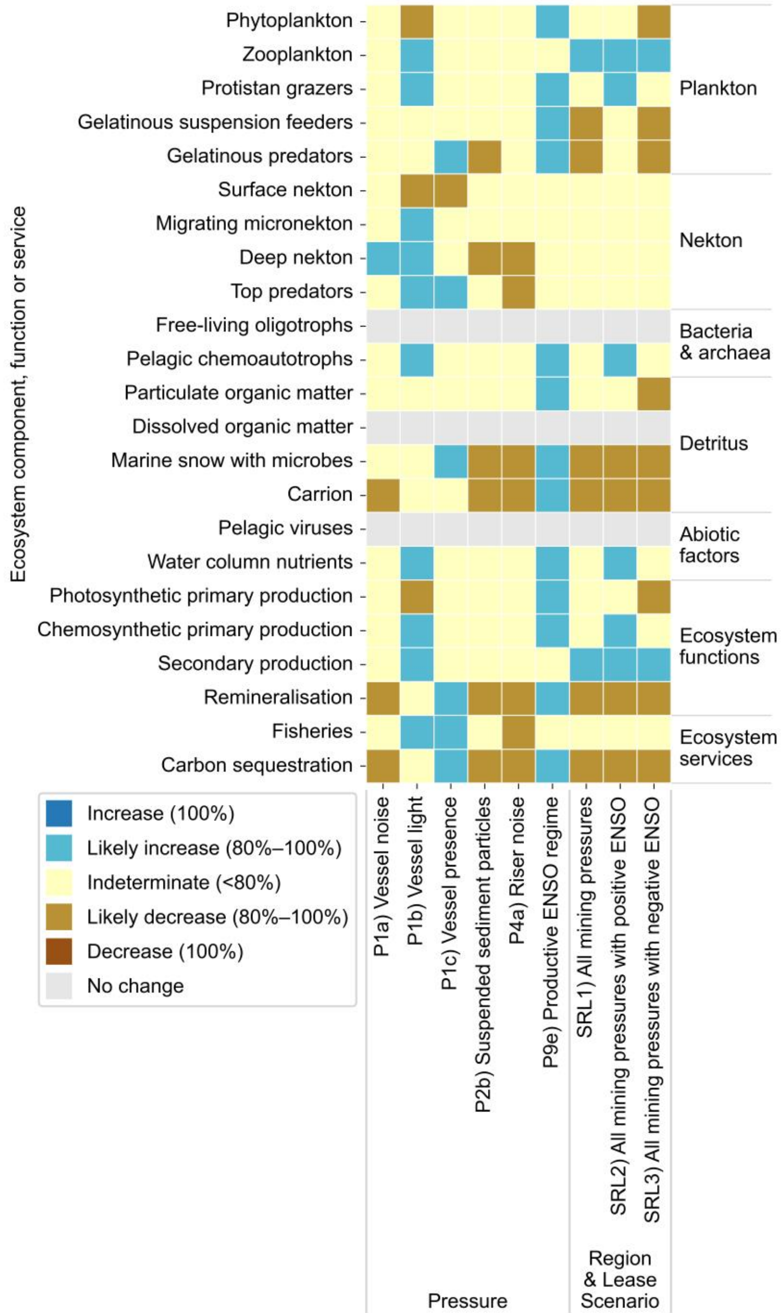


Figure 7. Qualitative predictions of change for components of pelagic ecosystem (Fig. 3) in Project Zero in regional- and lease-level perturbation scenarios with a limited set of mining and non-mining related activities and pressures, as detailed in Appendix Table 7.

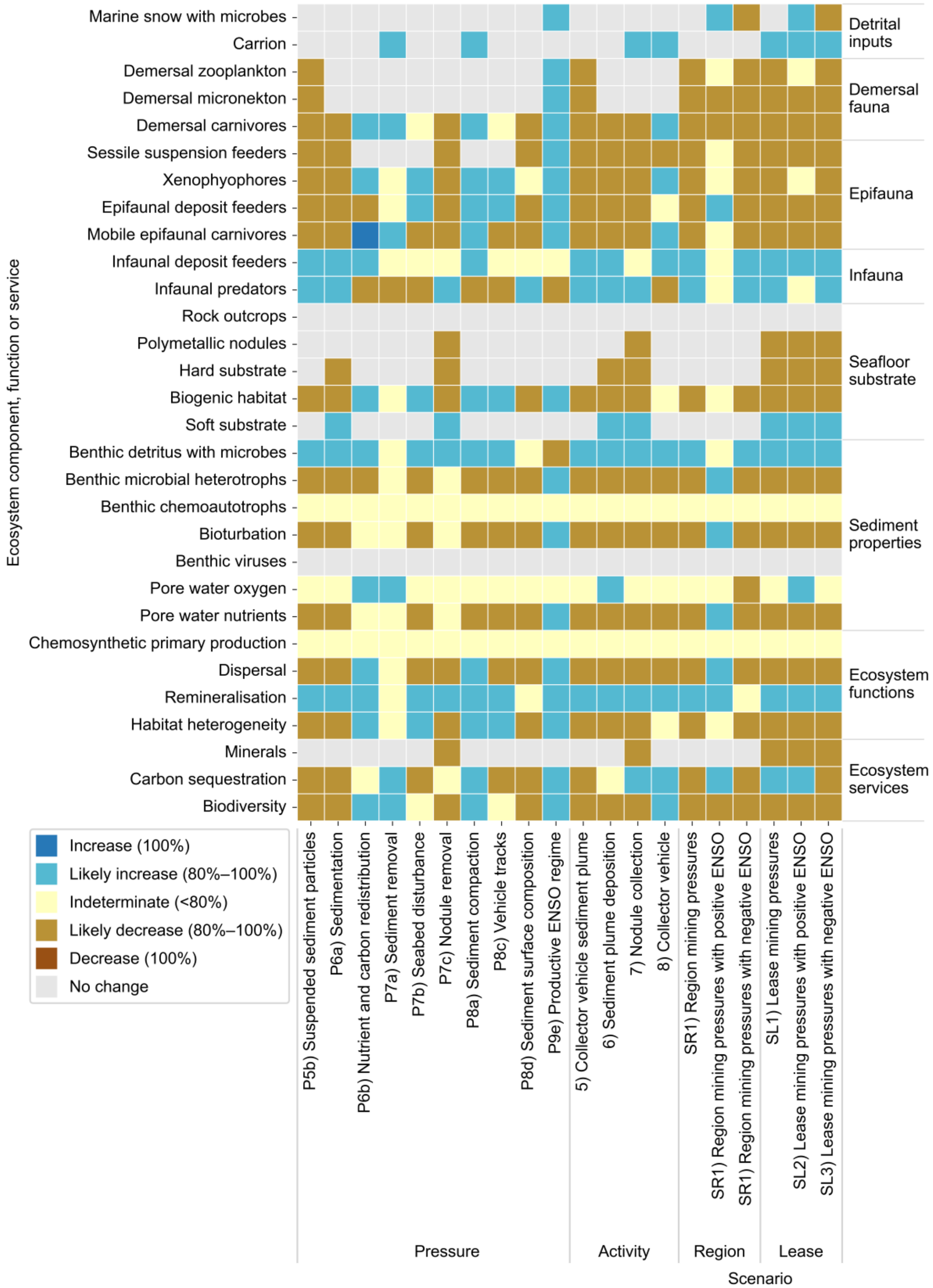


Figure 8. Qualitative predictions of change for components of benthic ecosystem (Fig. 3) in Project Zero in regional- and lease-level perturbation scenarios with a limited set of mining and non-mining related activities and pressures, as detailed in Appendix Table 7.

3.6 Candidate indicators

The worst-case perturbation scenarios for the pelagic and benthic ecosystem models readily support the identification of interpretable response predictions that can lead to the development of informative indicators for the monitoring and management of polymetallic nodule mining in the CCZ. Considering only the perturbation scenarios for mining operations (Table 3), there a total 13 candidate indicators for the pelagic ecosystem and 18 for the benthic ecosystem. For project zero perturbation scenarios, there was a relatively greater degree of ambiguity for response predictions in the pelagic ecosystem, with only three candidate indicators identified, while the benthic ecosystem had a total of 17.

Table 3. Candidate indicators identified in analyses of perturbation scenarios for the worst-case in the pelagic (Fig.5) and benthic (Fig. 6) ecosystem models, and Project Zero scenarios (Fig. 7 and 8), as marked by asterisks.

Pelagic ecosystem	Benthic ecosystem
carrion*	benthic detritus with microbes*
deep nekton	benthic microbial heterotrophs*
free-living oligotrophs	biogenic habitat*
gelatinous predators	bioturbation*
gelatinous suspension feeders	demersal carnivores*
marine snow with microbes*	demersal micronekton*
migrating micronekton	demersal zooplankton*
pelagic chemoautotrophs	epifaunal deposit feeders*
pelagic viruses	hard substrate*
protistan grazers	infaunal deposit feeders*
surface nekton	infaunal predators*
top predators	mobile epifaunal carnivores*
zooplankton*	polymetallic nodules*
	pore water nutrients*
	pore water oxygen
	sessile suspension feeders*
	soft substrate*
	xenophyophores*

4 Summary

- To meet the needs of identifying informative indicators for the DPSIR framework, qualitative mathematical models were developed through expert elicitation workshops that describe the biotic and abiotic components and processes of pelagic and benthic ecosystems of the CCZ, and potential pressures that might affect them associated with mining and non-mining activities and sources.
- Participants of the expert elicitation workshops were selected and invited based on their publication record in peer-reviewed journals on subjects relevant to deep-sea ecosystem biology and processes.
- The downward transfer of organic matter is the primary process that links the pelagic and benthic ecosystems; by contrast no significant processes or effects propagate upwards from abyssal depths.
- Qualitative model predictions were found to be highly consistent with known dynamics associated with light attenuation in the pelagic ecosystem.
- Sets of pressures and pressure scenarios were developed to assess impacts from deep-sea mining activities and other non-mining activities and sources.
- Qualitative analyses of pressure scenarios were used to identify sets of informative indicators that can potentially serve as candidate indicators for the purpose of monitoring and management of deep-sea mining activities.

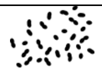
5 Appendix Tables

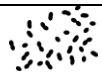
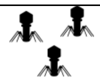
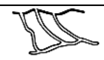
Table 4. Node names and abbreviations in signed digraph models developed in expert elicitation workshops (Fig. 1 and 2) and those in revised model (Fig. 3); multiple nodes within row were aggregated into single node in revised model based on similarity of biological and physical processes and functions.

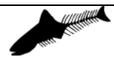
Node name revised model	Node name & abbr London workshop	Node name & abbr Long Beach workshop
Benthic chemoautotrophs	MA: microbial autotrophs	
Benthic detritus with microbes	POM DOM: particulate organic matter and dissolved organic matter	Epibenthic POM: epibenthic particulate organic matter Near surface microbial comm: near surface microbial community
Benthic microbial heterotrophs	PH: prokaryotic heterotrophs EH: eukaryotic heterotrophs	
Benthic viruses	Vir: viruses	
Biogenic habitat	BH: biogenic habitat	
Bioturbation	Bioturbation Bioirrigation	
Carrion	Car: carrion	Car: carrion
Deep nekton		NMMn: non-migrating micronekton
Demersal carnivores	DPS: demersal predators and scavengers	MS: mobile scavengers
Demersal micronekton		Demersal micronekton
Demersal zooplankton	ZP: zooplankton	HP: holoplankton MP: meroplankton Larval escapees
Dissolved organic matter		DOM: dissolved organic matter
Epifaunal deposit feeders	MEPD: mobile epifauna POM and DOM feeders	DF: deposit feeders MF: microbial feeders
Free-living oligotrophs		SH: Starving heterotrophs
Gelatinous predators		GZp: gelatinous zooplankton
Gelatinous suspension feeders		GSF: gelatinous suspension feeder
Hard substrate		Hard substrate
Infaunal deposit feeders	IPD: infauna POM and DOM feeders	
Infaunal predators	IP: infauna predators	
Marine snow with microbes		Marine snow and MH: marine snow and microbial heterotrophs Aging POM MH: ageing particulate organic matter and microbial heterotrophs
Migrating micronekton		MMn: migrating micronekton
Mobile epifaunal carnivores	MEC: mobile epifauna carnivores	Mobile carnivores
Particulate organic matter		POM: particulate organic matter

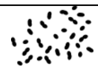
Node name revised model	Node name & abbr London workshop	Node name & abbr Long Beach workshop
Pelagic chemoautotrophs		Ca: chemoautotrophs
Pelagic viruses		Vir: viruses
Phytoplankton		SPP: small phytoplankton
Polymetallic nodules	Nodules	Nod: nodules
Pore water nutrients	PWN: pore water nutrients	
Pore water oxygen	O_2: oxygen	
Protistan grazers		SZp: small zooplankton
Rock outcrops		Rock outcrops
Sessile suspension feeders	SEPD: sessile epifauna POM and DOM feeders SEP: sessile epifauna predators	SFH: suspension feeders on hard substrate
Soft substrate	Benthic space	
Surface nekton		EF: epipelagic fishes
Top predators		EP: epipelagic predators
Water column nutrients		DN: dissolved nutrients
Xenophyophores	XF: xenophyophores	SFS: suspension feeders on soft substrate
Zooplankton		ZP: zooplankton
Note: omitted from revised model; did not contribute to model dynamics.	Convex topo: convex topography	
Note: omitted from revised model; now incorporated as a pressure.	Compaction	
Note: omitted from revised model; this variable was a placeholder for subsystem detailed in Fig. 1b.	MC: microbial community	
Note: omitted from revised model; accounted for as negative input to phytoplankton from light attenuation that is represented in model structure and dynamics.		Depth
Note: omitted from revised model; did not contribute to model dynamics.		Depth at seafloor

Table 5. Definition of signed digraph model (Fig. 3) nodes and abbreviations.

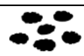
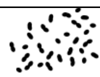
Node name	Abbr	Definition	Icon
Benthic chemoautotrophs	BCa	Benthic chemosynthetic protists inhabit soft and hard substrate at the seafloor, as well as the bottom seawater just above the seafloor. They obtain their energy through chemosynthesis, a process by which they convert inorganic chemical compounds into organic matter (Hollingsworth *et al.* 2021, Nomaki *et al.* 2021, Wear *et al.* 2021). Similar rates of chemosynthetic production have been observed between the Clarion-Clipperton Zone and the Peru Basin (Sweetman *et al.* 2019, Vonnahme *et al.* 2020).	

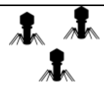
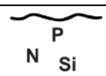
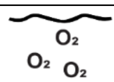
Node name	Abbr	Definition	Icon
Benthic detritus with microbes	BD	Labile and semi-labile particulate organic matter that has settled on abyssal plains after sinking through the water column. Abyssal plains are food-limited (<1% of net primary production in oligotrophic ocean waters), although biomass, abundance and diversity of benthic fauna, across all size classes, is strongly modulated by spatial and temporal variations in the flux of phytodetritus to the seafloor, indicating bottom-up control (Smith *et al.* 2008, Turner 2015). The quality and quantity of organic matter varies spatially primarily due to water column processes, and heterogeneous sedimentation patterns are observed at the seafloor resulting from topographic variations and associated bottom water currents (Nomaki *et al.* 2021, Volz *et al.* 2018). Dissolved organic matter is also higher in sediment pore waters compared to bottom water since it is an intermediate process after the breakdown of fresh phytodetritus before remineralisation by benthic microbial communities (Paul *et al.* 2018). Phytodetritus may arrive at the abyssal seafloor in pulses (Lampitt *et al.* 2001), which are often difficult to measure, and in the Clarion-Clipperton Zone, and some benthic biota are more responsive to these short-term pulses (Chatzievangelou *et al.* 2020, Enge *et al.* 2011, Sweetman *et al.* 2019, Thomsen *et al.* 2017). Sessile sponges at seamounts and the abyssal seafloor may also produce detritus by assimilating dissolved organic matter and detrital material (Bart *et al.* 2021, de Goeij *et al.* 2013).	
Benthic microbial heterotrophs	BMH	Benthic heterotrophic bacteria and archaea that inhabit soft and hard substrate of the seafloor. They obtain their energy by assimilating particulate and dissolved organic matter. Nodules, seafloor sediment and subseafloor sediments have distinct microbial communities and their composition changes across a subtle east-to-west gradient in the Clarion-Clipperton Zone (Bienhold *et al.* 2016, Kallmeyer *et al.* 2012, Shulse *et al.* 2017, Tully and Heidelberg 2013, Wear *et al.* 2021). These microorganisms play a crucial role in the decomposition of organic matter in the thin bioactive surface layer of abyssal sediments (De Jonge *et al.* 2020, Orcutt *et al.* 2020, Vonnahme *et al.* 2020) and can dominate short-term processing of phyto-detrital inputs (Sweetman *et al.* 2019).	
Benthic viruses	BV	Viruses that infect bacteria (phages) in seafloor sediments. Phages destroy host cells (lysis) and contribute to the dissolved organic matter pool in seafloor sediments (Breitbart *et al.* 2018, Stratmann 2023). Virus-induced bacterial lysis explains the fast prokaryotic turnover in abyssal sediments, despite severe food-limitation (Danovaro *et al.* 2008b, Nomaki *et al.* 2021).	
Biogenic habitat	BH	Biological substrate from living or dead sessile organisms on abyssal plains. Both living and dead biogenic structures increase habitat heterogeneity (Beaulieu 2001, Buhl-Mortensen *et al.* 2010); support feeding strategies for deposit feeders by concentrating organic matter (Hughes and Gooday 2004, Levin 1991, Levin and Thomas 1988), or providing access to bottom waters above the benthic boundary layer for suspension feeders (Beaulieu 2001, Buhl-Mortensen *et al.* 2010); provide nursery habitat for fish and octopods (Levin and Rouse 2020, Purser *et al.* 2016); and may host distinct microbial communities (de Goeij *et al.* 2013, Hori *et al.* 2013). Some of the major taxa include live and dead sponge stalks (Porifera) and xenophyophore tests (Foraminifera infraphylum), as well as black corals (Order Antipatharia), soft corals (Order Alcyonacea), crinoids (Class Crinoidea), anemones (Order Actiniaria) and sea pens (Order Pennatulacea). Both sponge stalks and xenophyophore tests are key structural species in the Clarion-Clipperton Zone (Gooday *et al.* 2021, Stratmann *et al.* 2021).	
Bioturbation	Biot	Sediment that has been reworked by sediment infauna and epifauna, including burrowing, ingestion, and defecation of sediment grains (Haffert *et al.* 2020; Volz *et al.* 2018, 2020). This process redistributes nutrients and organic matter within the sediment and can impact the	

Node name	Abbr	Definition	Icon
		structure of the benthic community (Volz *et al.* 2018). Bioturbation depths in the Clarion-Clipperton Zone are between 5-15 cm (Volz *et al.* 2018, 2020).	
Carrion	Car	Fast sinking carrion (food falls) originating from epipelagic and mesopelagic ocean waters. These food falls provide intermittent pulses of labile organic matter to abyssal plains. Sinking carrion provides high-quality food for a broad range of scavengers. Cetacean falls support distinct ecological communities that pass through multiple successional stages (Smith and Baco 2003), and have been observed in the Clarion-Clipperton Zone (Amon *et al.* 2017a, Smith *et al.* 2015). Other food falls also occur in the abyssal Pacific from large fishes, crustaceans (Simon-Lledó *et al.* 2023a), cephalopods (Hoving *et al.* 2022) and pyrosomes (Hoving *et al.* 2023). Sinking of these carcasses to the deep seafloor represents a key route that functionally couples shallower layers with food webs of the abyssal plains.	
Deep nekton	DN	Non-migrating nekton inhabiting mesopelagic and bathypelagic ocean waters, generally greater than 2 cm in size. These nekton are prey items of top predators. Diel vertical migration behaviour is uncommon, and grazing on zooplankton can occur throughout the day. Many species have a neotenic existence with infrequent feeding and low metabolic requirements (Drazen and Sutton 2017). Representative taxa include bristlemouths (Cyclothone), anglerfishes (Lophiiformes), hatchet fishes (Sternoptychidae) and some species of caridean shrimp (Caridea).	
Demersal carnivores	DC	Highly mobile scavengers and predators in abyssopelagic ocean waters. These demersal carnivores are mostly scavengers feeding on carrion falls from the upper water column, and live or dead epifauna are less frequent prey items (Leitner *et al.* 2017). Many are benthopelagic fishes that live in association with the seafloor but spend very little time in contact with it (Drazen and Sutton 2017, Gartner *et al.* 1997), as well as highly mobile benthic invertebrate scavengers (Drazen *et al.* 2021). Examples of representative taxa include grenadiers (Family Macrouridae), cusk-eels (Family Ophidiidae), cutthroat eels (Family Synaphobranchidae), eelpouts (Family Zoarcidae), and scavenging shrimp (Family Penaoidea and Genus Hymenopenaeus). Several baited camera studies and remotely operated vehicle visual transects have been conducted in the Clarion-Clipperton Zone to assess community composition and diversity (Drazen *et al.* 2021, Harbour *et al.* 2020, Leitner *et al.* 2017). Most observed scavengers have very large ranges (Drazen *et al.* 2021) and there is limited evidence to suggest that nodule cover influences diversity of demersal scavengers and none are nodule-obligate (Harbour *et al.* 2020, Leitner *et al.* 2017). Abyssal seamounts in the Clarion-Clipperton Zone have unique scavenger communities (Leitner *et al.* 2021).	
Demersal micronekton	DMn	Suspension feeding invertebrates living in the benthic boundary layer (< 200m above the seafloor). These invertebrates graze on zooplankton and suspended particles in the bottom water above the abyssal seafloor (Amon *et al.* 2017b, Christodoulou *et al.* 2022) and are the main prey of demersal carnivores (Drazen *et al.* 2008, Pearcy and Ambler 1974). Representative taxa include various shrimps and shrimp-like crustaceans (Infraorder Caridea and Order Mysida).	
Demersal zooplankton	DZp	Plankton in bottom waters in the benthic boundary layer, generally within 100m of the seafloor. These plankton can be designated either holoplankton with representative taxa including gelatinous zooplankton (Amon *et al.* 2017b, Robison 2004, Smith *et al.* 1992), such as ctenophores (Phylum Ctenophora) and scyphozoans (Phylum Ctenophora), or as meroplankton, which may include larval propagules from a range of benthic taxa (Kersten *et al.* 2019).	

Node name	Abbr	Definition	Icon
Dissolved organic matter	DOM	Labile and semi-labile dissolved organic matter in the water column. The contribution of dissolved organic carbon export to the carbon cycle decreases relative to particulate organic carbon export with increasing depths (Hansell *et al.* 2009). Semi-labile fractions of dissolved organic carbon are largely present in upper mesopelagic and epipelagic ocean waters, and most of the bathypelagic and abyssal dissolved organic carbon pool is refractory and is therefore reactive only on multi-millennial time scales (Dittmar *et al.* 2021, Wakeham and Lee 2019). The overall dissolved organic carbon reservoir in the ocean is greater than atmospheric carbon, and more than 200 times greater than the carbon inventory of global marine biomass (Hansell *et al.* 2009). In the equatorial Pacific, the reactive labile and semi-labile forms of dissolved organic carbon are largely present in the upper ocean (<500 m), and most forms in deep Pacific waters (>500m) are refractory and unreactive on multi-millennial time scales (Hansell *et al.*, 2009). Therefore, exported dissolved organic carbon supports only a small fraction of respiration in deeper waters compared to particulate organic carbon (Arístegui *et al.* 2002, Hansell *et al.* 2009).	
Epifaunal deposit feeders	EDF	Epibenthic deposit feeders living on the seafloor in abyssal plains that can be either mobile or sedentary. Larger epifauna (> 2cm) are often visible in imagery from seafloor photographs (Danovaro *et al.* 2020; Simon-Lledó *et al.* 2023a; Stratmann *et al.* 2018a). Mobile species can move across the seafloor feeding on deposits of particulate detritus and benthic microbial communities (Laming *et al.* 2021, Pierrat *et al.* 2022). Sedentary species collect and ingest adjacent deposits of benthic detritus, such as foraminifera which use reticulated pseudopodia for feeding (Gooday *et al.* 2021). Biogeographic patterns in the abundance of epifaunal deposit feeders are modulated by particulate organic carbon flux to the seafloor (Simon-Lledó *et al.* 2023b). Examples of representative taxa include sea cucumbers (Class Holothuria), urchins (Class Echinoidea), some brittle stars (Class Ophiuroidea) and Foraminifera. Many deposit feeders can also opportunistically change to suspension feeding. This food source will include come demersal nekton but also resuspended detritus.	
Free-living oligotrophs	FO	Free-living heterotrophic microbial communities inhabiting mostly mesopelagic and bathypelagic ocean waters. They grow by assimilating organic compounds from the oceans dissolved organic carbon reservoir, and are slow growing, surviving in nutrient deficient (oligrotrophic) ocean waters. This includes free-living bacteria, which occur as unattached cells suspended in the water column (Giovannoni *et al.* 2005, Giovannoni 2017, Rappé *et al.* 2002) and are distinct from particle-attached heterotrophic microbial communities (Salazar *et al.* 2015), photoautotrophs in the euphotic zone (DeLong *et al.* 2006), and chemoautotrophs in the disphotic zone (Swan *et al.* 2011). Archaea increase in abundance relative to bacteria cells with depth (Karner *et al.* 2001). Some prokaryotic heterotrophs are sensitive to pressure, which inhibits metabolic activity, especially in bathypelagic ocean waters (Amano *et al.* 2022). Bacterial community composition varies between epipelagic, mesopelagic and bathypelagic ocean waters in the Clarion-Clipperton Zone (Lindh *et al.* 2017, 2018). Representative taxa include bacteria (Order Pelagibacterales) and archaea (Phyla Euryarchaeota and Crenarchaeota).	
Gelatinous predators	GP	Predatory gelatinous zooplankton in epipelagic, mesopelagic and bathypelagic ocean waters. These gelatinous predators play a significant role in deep pelagic food webs (*i.e.*, the jelly web), feeding both on non-gelatinous zooplankton (*e.g.*, crustaceans) and other gelatinous zooplankton (Choy *et al.* 2017), and supporting attached microbial communities (Stenvers *et al.* 2023). The representative taxa are scyphozoans, siphonophores (Phylum Cnidaria) and ctenophores (Phylum Ctenophora). Bioluminescence is common in	

Node name	Abbr	Definition	Icon
		nearly all siphonophores and ctenophores, and many scyphozoans, and is used for both to avoid predation and to lure prey (Haddock *et al.* 2010).	
Gelatinous suspension feeders	GSF	Suspension feeding gelatinous zooplankton in epipelagic, mesopelagic and bathypelagic ocean waters. These gelatinous zooplankton feed on suspended particulate organic matter (Madin 1974). Representative taxa include salps, larvaceans, dolloids (Tunicata subphylum). Gelatinous suspension feeders provide unique ecological functions, such as salps which contribute to sinking marine snow via compact faecal pellets (Henschke *et al.* 2016, Turner 2015), and larvaceans which produce abandoned houses that serve as food sources for copepods (Alldredge 1972, Robison *et al.* 2005).	
Hard substrate	HS	Hard substrate, including rock and nodules, provides habitat heterogeneity in abyssal plains. Benthic fauna use hard substrate as an attachment surface (Vanreusel *et al.* 2016), microhabitat (Thiel *et al.* 1993), nursery habitat (Purser *et al.* 2016), shelter or foraging area. Polymetallic nodules partially replace soft substrate near the sediment surface, while rock outcrops can completely replace soft substrate in certain areas at the seafloor (Uhlenkott *et al.* 2023).	
Infaunal deposit feeders	IDF	Animals that live largely in the top layer of soft sediments below the surface and feed on organic matter contained within the sediments. These infauna feed on particulate organic matter and graze on microorganisms within the top 5 cm of abyssal sediments. Representative meiofaunal taxa include nematodes (Phylum Nematoda), copepods (Subclass Copepoda), kinorhynchs (Phylum Kinorhyncha) and foraminiferans (Infraorder Foraminifera). Nematodes are the dominant metazoan meiofaunal group in the Clarion-Clipperton Zone (Chuar *et al.* 2020, Hauquier *et al.* 2019, Lins *et al.* 2021, Tong *et al.* 2022, Zeppilli *et al.* 2018) and exhibit potentially low degrees of endemism and large distribution ranges (Pape *et al.* 2017). Foraminifera are also abundant deposit feeders in abyssal plains and potentially assimilate dissolved organic matter (Goineau and Gooday 2017; Gooday *et al.* 1992, 2008, 2021). Tube-dwelling fauna, such as polychaetes and tanaids, are a key deposit-feeding macrofauna in the Clarion-Clipperton Zone (Janssen *et al.* 2019, Stewart *et al.* 2023, Washburn *et al.* 2021b). Some macrofaunal isopods are also deposit-feeders (Błażewicz *et al.* 2019, Kaiser *et al.* 2023). Representative macrofaunal taxa include sediment-dwelling brittle stars (Class Ophiuroidea), polychaetes (Annelida phylum), isopods (Arthropoda phylum), tanaids (Arthropoda phylum) and gastropods (Mollusca phylum).	
Infaunal predators	IP	Predatory meiofauna and macrofauna inhabit seafloor sediments in abyssal plains and prey on other infauna within the top 5 cm of abyssal sediments. Representative macrofaunal taxa include sediment polychaetes (Annelida), sediment-dwelling isopods (Arthropoda phylum) and gastropods (Mollusca phylum). Polychaetes and ophiuroids are the dominant predatory macrofaunal taxa in the Clarion-Clipperton Zone (Christodoulou *et al.* 2020, Janssen *et al.* 2019, Kaiser *et al.* 2023, Stewart *et al.* 2023, Washburn *et al.* 2021a, Wiklund *et al.* 2017), while nematodes are representative of meiofauna predators.	
Marine snow with microbes	MS	Aggregations of particulate organic matter in mesopelagic and bathypelagic ocean waters. These particles are derived from a variety of sources (Boyd *et al.* 2019, Turner 2015, Wakeham and Lee 2019), such as phytodetritus in the upper water column usually >200 µm in diameter (Suess 1980), as well as migrating zooplankton (Steinberg *et al.* 2008), faecal pellets (Henschke *et al.* 2016, Wilson *et al.* 2013) and several other sources. Larger particles without ballast material (such as faecal pellets) have slower sinking rates and can form unique microhabitats for particle-attached microbial communities (Bochdansky *et al.* 2016). These microbial communities are consumed by particle-attached protozoans throughout the water	

Node name	Abbr	Definition	Icon
		column, such as heterotrophic flagellates (Gooday *et al.* 2020, Patterson *et al.* 1993, Turley *et al.* 1988). The sinking flux of organic matter decreases with depth, and becomes more refractory (and difficult to characterise molecularly). Most of the change in composition occurs in mesopelagic ocean waters (Wakeham and Lee 2019). Export of organic matter to deep ocean waters is mostly attenuated by microbial colonisation and zooplankton feeding.	
Migrating micronekton	MMn	Highly mobile small fishes and invertebrates inhabiting mesopelagic ocean waters, generally ranging from 2 to 20cm in size (Brodeur and Yamamura 2005). Micronekton migrations may extend into upper bathypelagic ocean waters (Sutton 2013, Sutton *et al.* 2017). Diel vertical migration behaviour is common, moving to the surface at night to feed on zooplankton and returning to deeper waters during the day to avoid predation (Aguzzi and Company 2010, Chatzievangelou *et al.* 2021, Drazen and Sutton 2017, Vereshchaka 1995). Diel vertical migration behaviour varies in strength across the Clarion-Clipperton Zone (Perelman *et al.* 2021). Representative taxa include lanternfishes (Family Myctophidae), squids (Class Cephalopoda), krill (Order Euphausiacea), and some species of caridean shrimp (Infraorder Caridea).	
Mobile epifaunal carnivores	MEC	Mobile epibenthic carnivores living on the seafloor in abyssal plains. These megafauna (> 2cm) are visible in seafloor photographs (Harbour *et al.* 2020, Simon-Lledó *et al.* 2020), and mostly derive nutrition from live prey, or opportunistically feed on carrion (Harbour *et al.* 2020, Simon-Lledó *et al.* 2020, Stratmann *et al.* 2018a). Biogeographic patterns in species diversity and abundance have been observed across the Clarion-Clipperton Zone (Amon *et al.* 2016; Bribiesca-Contreras *et al.* 2021; Christodoulou *et al.* 2019, 2020; Simon-Lledó *et al.* 2023b) and are likely modulated by particulate organic carbon flux to the seafloor (Woolley *et al.* 2016). Examples of representative taxa include brittle stars (Class Ophiuroidea), sea-stars (Asteroides), sea-urchins (Echinoidea), decapods (Subphylum Crustacea), amphipods (Subphylum Crustacea) and isopods (Subphylum Crustacea).	
Particulate organic matter	POM	Suspended particles of organic matter (non-living) with particle-attached heterotrophic microbial communities (living) in epipelagic and mesopelagic ocean waters. Particulate organic matter is traditionally defined based on filtration methods that have used filters with a pore size of 0.45 µm. Phytoplankton are the most important source of particulate organic matter in the euphotic zone where light and nutrient availability drives the biological gravitational pump (Boyd *et al.* 2019). Particle-attached microbial communities are dominated by heterotrophic bacteria, followed by archaea and metazoa (Azam and Malfatti 2007, Boeuf *et al.* 2019). In the twilight zone, particulate organic carbon flux decreases with depth due to microbial remineralisation (Buesseler *et al.* 2007), and the macromolecular composition of particles becomes more difficult to characterise (Lee *et al.* 2004, Wakeham *et al.* 1997). Microbial communities tend to have a more surface-attached habit with increasing depth (DeLong *et al.* 2006). In the Clarion-Clipperton Zone, POC flux decreases from east to west, and from south to north (Lutz *et al.* 2007, Pennington *et al.* 2006).	
Pelagic chemoautotrophs	PCa	Communities of microbial chemoautotrophs (bacteria and archaea) inhabiting mostly mesopelagic and bathypelagic ocean waters. These microbes fix dissolved inorganic carbon into organic carbon with chemical enzymatic reactions (Nagata *et al.* 2010, Swan *et al.* 2011). Representative taxa include ammonia-oxidising archaea, nitrite-oxidising bacteria and sulphur-oxidising bacteria in the deep ocean (Könneke *et al.* 2014, Pachiadaki *et al.* 2017). Archaea increase in relative abundance to bacteria cells with increasing water depth (Karner *et al.* 2001) and can thrive in nutrient-limited environments	

Node name	Abbr	Definition	Icon
		in the open ocean due to efficient chemoautotrophic processes (Könneke *et al.* 2014).	
Pelagic viruses	PV	Viruses that infect bacteria (phages) throughout the water column. Phages destroy host cells (lysis) and thereby produce particulate and dissolved organic matter (Breitbart *et al.* 2018). In a process called the viral shunt, the resulting dissolved organic matter is remineralised by microbes, keeping carbon in surface waters (Shiah *et al.* 2022). Viruses influence phytoplankton production, biogeography and biogeochemistry in epipelagic ocean waters (Carlson *et al.* 2022, Suttle *et al.* 1990). The ratio of viruses to prokaryotes generally increases with depth (De Corte *et al.* 2012).	
Phytoplankton	Pp	Free-floating photosynthetic organisms inhabiting epipelagic ocean waters. Sunlight and inorganic nutrients are required for growth, supplying photosynthetically-fixed carbon to marine heterotrophs (Biller *et al.* 2015). Phytoplankton growth occurs in the euphotic zone, primarily above 100 m water depth in the Clarion-Clipperton Zone (Wang *et al.* 2022), and is attenuated with depth in mesopelagic ocean waters (Herring 2001, Jerlov 1968). Primary production in the eastern tropical Pacific is generally higher than the other areas of the Pacific and global means (Pennington *et al.* 2006). Representative taxa include Prochlorococcus (Chisholm *et al.* 1988) and Synechococcus (Waterbury *et al.* 1979) (Phylum Cyanobateria). Prochlorococcus are well-suited to oligotrophic ocean waters (Biller *et al.* 2015, Partensky and Garczarek 2010) with higher average cell abundance than Synechococcus in the equatorial Pacific (Flombaum *et al.* 2013).	
Polymetallic nodules	Nod	Polymetallic nodules, which provide the most abundant form of hard substrate on abyssal plains in the mining area of interest, form through hydrogenetic and diagenetic processes on, or just below, the sediment-water interface (mostly <10 cm sediment depth) and are found in certain parts of all oceans (Dutkiewicz *et al.* 2020, Hein *et al.* 2020). They consist primarily of precipitated iron oxyhydroxides and manganese oxides which accumulate metals such as nickel, cobalt, copper and rare earth elements from overlying and pore waters (Hein *et al.* 2020, Kuhn *et al.* 2017) and are the target of potential deep-sea mining operations. Nodule abundance, size and surface texture are all possible factors influencing the density, diversity and composition of faunal communities on the seafloor (Amon *et al.* 2016; McQuaid 2020; Simon Lledo 2019; Stratmann *et al.* 2021; Uhlenkott *et al.* 2023; Veillette *et al.* 2007a, 2007b). Nodule presence is particularly important for sessile epifauna that use nodules as an attachment surface (Stratmann *et al.* 2021, Vanreusel *et al.* 2016), and encrusting organisms (mainly Foraminifera) that live in the millimetre-scale crevices on nodule surfaces (Thiel *et al.* 1993), but may negatively influence the abundance of infauna that inhabit soft sediments (Pape *et al.* 2021).	
Pore water nutrients	PWN	The concentration of inorganic nutrients in the water that occupies the spaces between sediment particles on the seafloor. Inorganic nutrients such as nitrate, phosphate and silicate, support chemosynthetic production by microbial communities (Paul *et al.* 2018, Sweetman *et al.* 2019, Volz *et al.* 2018, Vonnahme *et al.* 2020).	
Pore water oxygen	PWO	The concentration of dissolved oxygen in the water that occupies the spaces between sediment particles on the seafloor. Abyssal sediments are characterised by low organic matter and high oxygen (Nomaki *et al.* 2021), especially in the Clarion-Clipperton Zone, with oxygen penetration depths greater than 1m (Volz *et al.* 2018). Upward diffusion from basaltic crust can make sediments completely oxic (Versteegh *et al.* 2021).	

Node name	Abbr	Definition	Icon
Protistan grazers	PG	Heterotrophic protists (protozoa) inhabiting mostly mesopelagic ocean waters. These microzooplankton (<0.2 mm) graze on bacteria and archaea (Gooday *et al.* 2020, Steinberg and Landry 2017), releasing regenerated nitrogen, phosphorus and iron (Barbeau *et al.* 1996), and are the prey of metazoans, thus transferring biomass from deep ocean microbes back to shallow ocean waters via the microbial loop (Azam 1998, Azam and Malfatti 2007). Protozoa make up a considerable contribution to zooplankton biomass throughout the oceans and a higher proportion in oligotrophic areas, including the equatorial Pacific Ocean (Biard *et al.* 2016). Representative taxa include a range of unicellular eukaryotes (Foraminifera, Radiolaria, Flagellates and Ciliates).	
Rock outcrops	RO	Rock outcrops contribute to habitat heterogeneity in deep-sea ecosystems. Rock outcrops, often located at the summits of abyssal hills, are surrounded by areas with varying coverage and size of polymetallic nodules (Uhlenkott *et al.* 2023). Rocky abyssal hills not only provide hard substrate for attachment of sessile fauna, but also may provide a three-dimensional structure that is more rugose than nodules (Jones *et al.* 2021, Mejía-Saenz *et al.* 2023). Differences between flow regimes and detrital inputs suggest that both abyssal hills favour suspension feeders such as corals and sponges (Durden *et al.* 2015, Schlacher *et al.* 2014), while abyssal plain areas favour deposit feeders (Durden *et al.* 2017).	
Sessile suspension feeders	SSF	Sessile fauna feeding on suspended particles of marine snow and attached microbial communities in the bottom waters above abyssal plains. Most taxa and individuals are attached to hard substrate (*i.e.* polymetallic nodules or rocks), and can be elevated above the substratum (stalked) or grow on its surface (encrusting). Nodules appear to be an important habitat feature, and nodule-free sediments typically have the lowest density and diversity of observed epifauna (Lim *et al.* 2017, Stratmann *et al.* 2021, Taboada *et al.* 2018, Uhlenkott *et al.* 2023, Vanreusel *et al.* 2016). Regional biogeography arising from changes in seafloor bathymetry, particulate organic carbon flux, and carbonate compensation depth also influence the density and diversity of suspension-feeding species across the Clarion-Clipperton Zone (McQuaid 2020, Molodtsova and Opresko 2017, Simon-Lledó *et al.* 2023b). Representative taxa include sponges (Phylum Porifera), black corals (Order Antipatharia), soft corals (Order Alcyonacea), anemones (Order Actiniaria), sea pens (Order Pennatulacea), crinoids (Class Crinoidea) and other invertebrates (including Phylum Bryozoa). Some annelids inhabiting soft sediment also feed on suspended particles, although this is the least common feeding mode of this group (Stewart *et al.* 2023). Sessile organisms are also host to numerous epizoic animals that are also mainly suspension feeders.	
Soft substrate	SS	Fine sediments are the most common substrate-type in abyssal plains. Most abyssal sediments consist of terrigenous particles from rock weathering on land and biological particles from planktonic organisms (Dutkiewicz *et al.* 2015, Ramirez-Llodra *et al.* 2010). Sediment particles are mostly inorganic, except for a thin surface layer of organic detritus (Ramirez-Llodra *et al.* 2010), although biogenic oozes are common in some areas of the CCZ (Dutkiewicz *et al.* 2015, Washburn *et al.* 2021b). Abyssal plains contain areas that are nodule-free. Current evidence suggest that these bare sediments have lower densities of megafauna (Uhlenkott *et al.* 2023), comparable densities of macrofauna (Francesca *et al.* 2021) and higher densities of meiofauna (Pape *et al.* 2021), while microbial life is harder to quantify.	
Surface nekton	SN	Smaller predatory fishes and invertebrates inhabiting epipelagic ocean waters, generally greater than 2 cm in size. These nekton are prey items of top predators. Most forage in the euphotic zone, and few species deep dive to forage (Choy *et al.* 2015, Van Noord *et al.*	

Node name	Abbr	Definition	Icon
		2013a). Representative taxa include flying fishes (Family Exocoetidae), small jack mackerel (Family Carangidae)	
Top predators	TP	Large marine predators inhabiting epipelagic ocean waters. Deep diving behaviour is common for foraging, predator avoidance, navigation, and energy conservation (Braun *et al.* 2022). Most do not exceed a maximum average dive depth of 1,000 m, except for the sperm whale (Braun *et al.* 2022). Migration pathways differ among species and are seasonal, with several traversing the Clarion-Clipperton Zone in the Pacific Ocean (Block *et al.* 2011). Representative taxa include tuna, mackerel, and bonito (Family Scombridae); dolphin fishes (Genus Coryphaena); marlins and swordfishes (Order Istiophoriformes); tripletails (Order Percomorpha); albatrosses and petrels (Order Procellariiformes); gannets and cormorants (Order Suliformes); whales and dolphins (Infraorder Cetacea); and sea turtles (Superfamily Chelonioidea). Key species in the central-eastern Pacific Ocean include dolphin fishes, yellowfin tuna, skipjack tuna and tripletails (Dambacher *et al.* 2010).	
Water column nutrients	WCN	Inorganic nutrients distributed throughout the water column. Key macronutrients include nitrogen, phosphorus and silica. Key micronutrients include iron, cobalt, and zinc. Phytoplankton and other microbes assimilate nutrients in the euphotic zone, which leads to nutrient depletion in surface waters; as phytoplankton growth is attenuated with depth, microbes mineralise this particulate organic matter, enhancing nutrient concentrations below the euphotic zone (Arrigo 2005, Moore *et al.* 2013). Iron, nitrogen and phosphorus typically limit phytoplankton growth throughout the global ocean (Moore *et al.* 2013) and iron is a key limiting nutrient in the equatorial Pacific Ocean (Coale *et al.* 1996, Moore *et al.* 2013, Saito *et al.* 2014, Tagliabue *et al.* 2017).	**P** **N** **Fe**
Xenophyophores	Xp	Giant agglutinating protozoans living on the seafloor on abyssal plains. Xenophyophores are fast colonisers of hard as well as soft substrate and have wide dispersal and geographic ranges (Alve and Goldstein 2003, Gooday *et al.* 2021). There is evidence to suggest landscape-type variations have an influence on standing stocks (Simon Lledo 2019), and nodule presence may be a driver of diversity (Gooday *et al.* 2018a, 2018b). Xenophyophores on hard substrate are most likely suspension feeders, and those on soft substrate are likely to be deposit feeders (Gooday *et al.* 2017). There is also evidence that xenophyophores assimilate dissolved organic matter (Levin and Gooday 1992, Tsuchiya and Nomaki 2021). Despite being unicellular, they are among the most abundant epifauna visible from seafloor photography and video in the Clarion-Clipperton Zone (Simon Lledo 2019) and their tests provide important biogenic habitat on abyssal plains (Levin 1991).	
Zooplankton	Zp	Heterotrophic mesozooplankton inhabiting epipelagic and mesopelagic ocean waters, generally ranging in 0.2 to 20mm in size. Vertical migration behaviour is common, moving towards the surface at night to graze on phytoplankton, and returning to deeper waters during the day to avoid predators (Hays 2003). Diel vertical migration behaviour varies in strength across the Clarion-Clipperton Zone (Perelman *et al.* 2021). Vertical migrators are strongly affected by vertical oxygen gradients of oxygen minimum zones (Wishner *et al.* 2018). Key prey items are phytoplankton, forming the main pathway of secondary production (Steinberg and Landry 2017). This process transfers energy to higher trophic levels (Ratnarajah *et al.* 2023), generates dissolved organic matter via inefficient feeding, produces fast-sinking faecal pellets (Turner 2015, Wilson *et al.* 2013) and increases sinking rates of marine snow (Boyd *et al.* 2019). Representative taxa include copepods (Subphylum Crustacea) and some krill (Order Euphausiacea).	

Table 6. Definition ecosystem processes, effects and links of signed digraph model (Fig. 3).

Effect to	Effect from	Sign	Definition
Benthic chemoautotrophs	Benthic microbial heterotrophs	Negative	Mortality by predation (Shulse *et al.* 2017, Wear *et al.* 2021)
Benthic chemoautotrophs	Benthic viruses	Negative	Mortality by viral lysis (Danovaro *et al.* 2008a, Nomaki *et al.* 2021)
Benthic chemoautotrophs	Pore water nutrients	Positive	Assimilation of inorganic nutrients for chemosynthesis (Sweetman *et al.* 2019)
Benthic detritus with microbes	Benthic microbial heterotrophs	Negative	Degradation of sediment organic matter (Sweetman *et al.* 2019)
Benthic detritus with microbes	Benthic viruses	Positive	Mortality of heterotrophic microbial communities by viral lysis and slowed degradation of organic matter (Danovaro *et al.* 2008a, Nomaki *et al.* 2021)
Benthic detritus with microbes	Carrion	Positive	Decomposition of carrion into particulate detritus by scavengers (Smith and Baco 2003)
Benthic detritus with microbes	Epifaunal deposit feeders	Negative	Mineralisation of sediment organic matter (De Jonge *et al.* 2020; Durden *et al.* 2019; Stratmann *et al.* 2018b, 2023)
Benthic detritus with microbes	Infaunal deposit feeders	Negative	Mineralisation of sediment organic matter (De Jonge *et al.* 2020, Schratzberger and Ingels 2018, Stratmann *et al.* 2018b, Tong *et al.* 2022)
Benthic detritus with microbes	Marine snow with microbes	Positive	Settling of marine snow on the seafloor (Hoving *et al.* 2023, Lampitt *et al.* 2001, Nomaki *et al.* 2021, Smith *et al.* 2008)
Benthic detritus with microbes	Sessile suspension feeders	Positive	Assimilation of dissolved organic matter by Porifera and conversion to sponge-derived particulate detritus (Bart *et al.* 2021, de Goeij *et al.* 2013)
Biogenic habitat	Sessile suspension feeders	Positive	Provision of biogenic habitat from sponge stalks and other sessile fauna (Stratmann *et al.* 2021)
Biogenic habitat	Xenophyophores	Positive	Provision of biogenic habitat from xenophyophore tests (Levin and Thomas 1988)
Benthic microbial heterotrophs	Benthic chemoautotrophs	Positive	Nutrition from predation (Shulse *et al.* 2017, Wear *et al.* 2021)
Benthic microbial heterotrophs	Benthic detritus with microbes	Positive	Nutrition from consumption of sediment organic matter (Sweetman *et al.* 2019)
Benthic microbial heterotrophs	Benthic viruses	Negative	Mortality by viral lysis (Danovaro *et al.* 2008a, Nomaki *et al.* 2021)
Benthic microbial heterotrophs	Bioturbation	Positive	Flushing of bioturbated sediment with dissolved organic matter and oxygen for heterotrophic microbial communities (Volz *et al.* 2018, 2020)
Benthic microbial heterotrophs	Pore water oxygen	Positive	Respiration of dissolved oxygen by microbial respiration (Jørgensen *et al.* 2022, Sweetman *et al.* 2019)
Bioturbation	Epifaunal deposit feeders	Positive	Reworking of surface sediments by movement across the seafloor (Ruhl 2007, Vardaro *et al.* 2009)
Bioturbation	Infaunal deposit feeders	Positive	Reworking of surface sediments by burrowing (Schratzberger and Ingels 2018)

Effect to	**Effect from**	**Sign**	**Definition**
Bioturbation	Infaunal predators	Positive	Reworking of surface sediments by burrowing (Schratzberger and Ingels 2018)
Bioturbation	Mobile epifaunal carnivores	Positive	Reworking of surface sediments by movement across the seafloor (Ruhl 2007, Tilot *et al.* 2018)
Carrion	Gelatinous predators	Positive	Flux of sinking carrion to the seafloor (Robison 2004)
Carrion	Gelatinous suspension feeders	Positive	Flux of sinking carrion to the seafloor (Robison *et al.* 2005)
Carrion	Surface nekton	Positive	Flux of sinking carrion to the seafloor (Hoving *et al.* 2022, Simon-Lledó *et al.* 2023a)
Carrion	Top predators	Positive	Flux of sinking carrion to the seafloor (Smith and Baco 2003)
Demersal carnivores	Biogenic habitat	Positive	Provision of biogenic habitat for demersal fauna (Levin *et al.* 2020, Stratmann *et al.* 2021)
Demersal carnivores	Carrion	Positive	Nutrition from scavenging (Drazen *et al.* 2012, 2008)
Demersal carnivores	Demersal micronekton	Positive	Nutrition from predation (Drazen *et al.* 2008, Pearcy and Ambler 1974)
Demersal carnivores	Epifaunal deposit feeders	Positive	Nutrition from predation, mostly consuming polychaetes or smaller deposit feeders, rather than holothurians or echinoids (Crabtree *et al.* 1991, Drazen and Sutton 2017, Massimo Perrone *et al.* 2003, Pearcy and Ambler 1974)
Demersal carnivores	Mobile epifaunal carnivores	Positive	Nutrition from predation (Crabtree *et al.* 1991, Drazen and Sutton 2017, Massimo Perrone *et al.* 2003, Pearcy and Ambler 1974)
Demersal micronekton	Demersal zooplankton	Positive	Nutrition from predation
Deep nekton	Migrating micronekton	Positive	Nutrition from predation (Choy *et al.* 2015, Drazen and Sutton 2017, McClain *et al.* 2001)
Deep nekton	Zooplankton	Positive	Nutrition from predation (Choy *et al.* 2015, Drazen and Sutton 2017)
Demersal zooplankton	Marine snow with microbes	Positive	Nutrition from suspension feeding particulate organic matter in the bottom water near the seafloor
Epifaunal deposit feeders	Benthic detritus with microbes	Positive	Nutrition from consumption of sediment organic matter (De Jonge *et al.* 2020; Durden *et al.* 2019; Smith *et al.* 1997; Stratmann *et al.* 2018b, 2023)
Epifaunal deposit feeders	Biogenic habitat	Positive	Provision of biogenic habitat for mobile epifauna (Levin 1991, Stratmann *et al.* 2021)
Free-living oligotrophs	Dissolved organic matter	Positive	Nutrition from assimilating dissolved organic matter (Carlson *et al.* 2004, Jiao *et al.* 2010, Logue *et al.* 2016, Pedler *et al.* 2014)
Free-living oligotrophs	Pelagic viruses	Negative	Mortality by viral lysis (Breitbart *et al.* 2018, Shiah *et al.* 2022)
Gelatinous predators	Gelatinous suspension feeders	Positive	Nutrition from predation (Choy *et al.* 2017, Robison 2004)
Gelatinous predators	Zooplankton	Positive	Nutrition from predation (Choy *et al.* 2017, Robison 2004)

Effect to	Effect from	Sign	Definition
Gelatinous suspension feeders	Particulate organic matter	Positive	Nutrition from filter feeding (Choy *et al.* 2017, Robison 2004)
Hard substrate	Polymetallic nodules	Positive	Provision of hard substrate from polymetallic nodules (Uhlenkott *et al.* 2023)
Hard substrate	Rock outcrops	Positive	Provision of hard substrate from rocky outcrops (Uhlenkott *et al.* 2023)
Infaunal deposit feeders	Benthic detritus with microbes	Positive	Nutrition from consumption of particulate organic matter or assimilation of dissolved organic matter (De Jonge *et al.* 2020, Pape *et al.* 2017, Smith *et al.* 1997, Stratmann *et al.* 2018b)
Infaunal deposit feeders	Infaunal predators	Negative	Mortality by predation (Kaiser *et al.* 2023, Stewart *et al.* 2023)
Infaunal deposit feeders	Mobile epifaunal carnivores	Negative	Mortality by predation (De Jonge *et al.* 2020, Stratmann *et al.* 2023)
Infaunal deposit feeders	Soft substrate	Positive	Provision of soft substrate as infauna habitat (Bonifácio *et al.* 2020, Pape *et al.* 2021, Washburn *et al.* 2021a)
Infaunal predators	Infaunal deposit feeders	Positive	Nutrition from predation (Gooday *et al.* 1992, Gudmundsson *et al.* 2000)
Infaunal predators	Mobile epifaunal carnivores	Negative	Mortality by predation (De Jonge *et al.* 2020, Stratmann *et al.* 2018b)
Infaunal predators	Soft substrate	Positive	Provision of soft substrate as infauna habitat (Bonifácio *et al.* 2020, Pape *et al.* 2021, Washburn *et al.* 2021a)
Mobile epifaunal carnivores	Biogenic habitat	Positive	Provision of biogenic habitat for mobile epifauna (Levin 1991, Stratmann *et al.* 2021)
Mobile epifaunal carnivores	Carrion	Positive	Nutrition from scavenging (Smith and Baco 2003)
Mobile epifaunal carnivores	Infaunal deposit feeders	Positive	Nutrition from predation (De Jonge *et al.* 2020, Stratmann *et al.* 2023)
Mobile epifaunal carnivores	Infaunal predators	Positive	Nutrition from predation (Simon-Lledó *et al.* 2020)
Mobile epifaunal carnivores	Xenophyophores	Positive	Nutrition from predation
Migrating micronekton	Zooplankton	Positive	Nutrition from predation (Drazen and Sutton 2017, Van Noord *et al.* 2013b)
Marine snow with microbes	Gelatinous predators	Positive	Export flux of mucus-based structures to the seafloor (Alldredge 1972, Robison *et al.* 2005)
Marine snow with microbes	Gelatinous suspension feeders	Positive	Export flux of faecal pellets and pyrosomes to the seafloor (Henschke *et al.* 2016, Hoving *et al.* 2023, Turner 2015)
Marine snow with microbes	Migrating micronekton	Positive	Export flux of migrating micronekton carrion to the seafloor (Boyd *et al.* 2019)
Marine snow with microbes	Particulate organic matter	Positive	Export of aggregated particles of organic matter from productive surface waters to deeper waters (Smith *et al.* 2008, Suess 1980)
Pelagic chemoautotrophs	Pelagic viruses	Negative	Mortality by viral lysis (Roux *et al.* 2014)

Effect to	Effect from	Sign	Definition
Pelagic chemoautotrophs	Water column nutrients	Positive	Assimilation of inorganic nutrients for chemosynthesis (Könneke *et al.* 2014, Pachiadaki *et al.* 2017)
Protistan grazers	Free-living oligotrophs	Positive	Nutrition from grazing (Azam and Malfatti 2007)
Protistan grazers	Pelagic chemoautotrophs	Positive	Nutrition from grazing (Azam and Malfatti 2007)
Protistan grazers	Pelagic viruses	Negative	Mortality by viral lysis (Breitbart *et al.* 2018)
Particulate organic matter	Pelagic viruses	Positive	Virus-mediated mortality of phytoplankton, aggregation of phytodetritus and mortality of particle-attached heterotrophic microbes (Wei *et al.* 2022, Yamada *et al.* 2020)
Particulate organic matter	Phytoplankton	Positive	Export flux of phytodetritus to the deep ocean (> 200m depth) below the photic zone (Riley 1971, Wakeham *et al.* 1997)
Particulate organic matter	Surface nekton	Positive	Decomposition of organisms and accumulation of particulate detritus in the surface ocean (Boyd *et al.* 2019)
Particulate organic matter	Top predators	Positive	Decomposition of organisms and accumulation of particulate detritus in the surface ocean (Boyd *et al.* 2019)
Particulate organic matter	Zooplankton	Positive	Transport of zooplankton detritus and faecal pellets to the deep ocean by vertical migrations (Boyd *et al.* 2019, Hernández-León *et al.* 2020, Turner 2015, Wakeham *et al.* 1997, Wilson *et al.* 2013)
Pore water nutrients	Benthic chemoautotrophs	Negative	Reduction in inorganic nutrients by chemosynthesis (Hollingsworth *et al.* 2021)
Pore water nutrients	Bioturbation	Positive	Flushing of inorganic nutrients into sediment pore water by bioirrigation (Volz *et al.* 2018)
Pore water oxygen	Benthic microbial heterotrophs	Negative	Reduction in dissolved oxygen from microbial respiration (Jørgensen *et al.* 2022, Sweetman *et al.* 2019)
Pore water oxygen	Bioturbation	Positive	Flushing of burrows in deep-sea sediments with overlying water (Volz *et al.* 2018, 2020)
Phytoplankton	Pelagic viruses	Negative	Mortality by viral lysis (Breitbart *et al.* 2018, Carlson *et al.* 2022, Coello-Camba *et al.* 2020, Mruwat *et al.* 2021, Suttle *et al.* 1990, Weitz and Wilhelm 2012)
Phytoplankton	Water column nutrients	Positive	Assimilation of inorganic nutrients for photosynthesis (Flombaum *et al.* 2013, Moore *et al.* 2013, Sigman and Hain 2012)
Phytoplankton	Zooplankton	Negative	Mortality by grazing (Steinberg and Landry 2017)
Surface nekton	Migrating micronekton	Positive	Nutrition from predation (Choy *et al.* 2015, Dambacher *et al.* 2010)
Surface nekton	Top predators	Negative	Mortality by predation (Alverson 1963, Choy *et al.* 2015, Dambacher *et al.* 2010, Markaida and Sosa-Nishizaki 1998, Olson *et al.* 2014)
Surface nekton	Zooplankton	Positive	Nutrition from predation (Van Noord *et al.* 2013a)
Soft substrate	Hard substrate	Negative	Replacement of soft substrate by hard substrate in the bioactive surface sediment layers (Parianos 2021, Uhlenkott *et al.* 2023)
Sessile suspension feeders	Demersal zooplankton	Positive	Nutrition from suspension feeding by passive capture (Vacelet and Boury-Esnault 1995)

Effect to	Effect from	Sign	Definition
Sessile suspension feeders	Hard substrate	Positive	Sites of attachment for sessile organisms (Amon *et al.* 2016, Mullineaux 1988, Simon-Lledo *et al.* 2019, Stratmann *et al.* 2021, Vanreusel *et al.* 2016)
Sessile suspension feeders	Marine snow with microbes	Positive	Nutrition from suspension feeding particulate organic matter in the bottom water near the seafloor (Pile and Young 2006; Simon-Lledó *et al.* 2023b; Stratmann *et al.* 2018b, 2021)
Top predators	Deep nekton	Positive	Nutrition from predation (Alverson 1963, Braun *et al.* 2022, Choy *et al.* 2015, Dambacher *et al.* 2010, Drazen and Sutton 2017, Olson *et al.* 2014)
Top predators	Migrating micronekton	Positive	Nutrition from predation (Alverson 1963, Braun *et al.* 2022, Choy *et al.* 2015, Dambacher *et al.* 2010, Drazen and Sutton 2017, Olson *et al.* 2014)
Top predators	Surface nekton	Positive	Nutrition from predation (Alverson 1963, Choy *et al.* 2015, Dambacher *et al.* 2010, Markaida and Sosa-Nishizaki 1998, Olson *et al.* 2014)
Water column nutrients	Pelagic viruses	Positive	Release of inorganic nutrients from viral lysis with potential precipitation of Fe by viruses (Daughney *et al.* 2004, Fuchsman *et al.* 2019, John *et al.* 2011, Weitz *et al.* 2015)
Water column nutrients	Phytoplankton	Negative	Assimilation of inorganic nutrients for photosynthesis (Saito *et al.* 2014)
Xenophyophores	Benthic detritus with microbes	Positive	Nutrition from consumption of sediment particulate and dissolved organic matter (Levin and Gooday 1992, Tsuchiya and Nomaki 2021)
Xenophyophores	Hard substrate	Positive	Sites of attachment for sessile organisms (Simon-Lledo *et al.* 2019)
Xenophyophores	Marine snow with microbes	Positive	Nutrition from suspension feeding particulate organic matter in the bottom water near the seafloor (Gooday *et al.* 2017, Tsuchiya and Nomaki 2021)
Zooplankton	Gelatinous predators	Negative	Mortality by predation (Choy *et al.* 2017)
Zooplankton	Migrating micronekton	Negative	Mortality by predation (Drazen and Sutton 2017)
Zooplankton	Protistan grazers	Positive	Nutrition from grazing (Azam and Malfatti 2007)
Zooplankton	Phytoplankton	Positive	Nutrition from grazing (Steinberg and Landry 2017)
Zooplankton	Surface nekton	Negative	Morality by predation (Van Noord *et al.* 2013a)

Table 7. Potential pressures described in expert elicitation workshops of proposed mining activities and other non-mining activities or sources and associated direct effects on specific components of signed digraph ecosystem model (Fig. 3). Activities, pressures and effects not included in Project Zero assessment are italicized; asterisks denote alternative terminology adopted by The Metals Company to describe or categorize pressures in their environmental assessment.

Activity/ source	Pressure	Code	Definition and measure	Spatial extent	Frequency during operations	Persistence after operations)	Potential to accumulate *in situ* over time	Potential to bio-accumulate	To	Code	Sign	Direct effect
1) Surface support vessel	Vessel noise *Noise	P1a	Decibels (dB) and frequency (Hz) of the noise field emanating from surface vessels	Dispersive	Continuous	Transient	No	No	Top predators	TP	–	Masking of communication and sensory distress
									Surface nekton	SN	–	Masking of communication and sensory distress
	Vessel light *Light	P1b	Wavelength (nm) and intensity (lumens) of light field emanating from surface vessels	Dispersive	Continuous	Transient	No	No	Surface nekton	SN	–	Emigration due to increased light
									Top predators	TP	+	Immigration due to increased light
	Vessel presence *Included as an activity but not a pressure	P1c	Presence of surface vessels (boat days per year) associated with a mining operation, including mining support vessels, transfer vessels for onshore processing and research vessels	Localised	Continuous	Transient	No	No	Top predators	TP	+	Fish attraction
2) Midwater sediment plume	*Water turbidity* **Water quality*	*P2a*	*Light scattering in seawater (NTU) from discharged sediment particles in the water column*	*Dispersive*	*Continuous*	*Transient*	*No*	*No*	*Top predators*	*TP*	–	*Feeding impairment*
									Gelatinous suspension feeders	*GSF*	–	*Feeding impairment*
									Protistan grazers	*PG*	–	*Feeding impairment*
									Migrating micronekton	*MMn*	–	*Reduced visual communication*
									Deep nekton	*DN*	–	*Reduced visual communication*
									Zooplankton	*Zp*	–	*Reduced visual communication*

Activity/ source	Pressure	Code	Definition and measure	Spatial extent	Frequency during operations	Persistence after operations)	Potential to accumulate *in situ* over time	Potential to bio-accumulate	To	Code	Sign	Direct effect
	Suspended sediment particles *Water quality	P2b	Total suspended solids in seawater (mg/L) from discharged sediment particles in the water column	Dispersive	Continuous	Transient	No	No	*Migrating micronekton*	*MMn*	–	*Respiration irritation*
									Deep nekton	DN	–	Respiration irritation
									Zooplankton	Zp	–	Respiration irritation
									Gelatinous predators	GP	–	Reduced buoyancy
									Gelatinous suspension feeders	GSF	–	Reduced buoyancy
	Suspended sediment flocculation	*P2c*	*The settling velocity of sediment particles (mm/s), where larger flocs (µm) tend to sink faster, which has an inverse effect on the horizontal diffusivity (m^2/s) of a midwater sediment plume (Munoz-Royo et al. 2021)*	*Dispersive*	*Continuous*	*Transient*	*No*	*No*	*Benthic detritus*	*BD*	+	*Co-precipitation and flocculation*
									Marine snow	*MS*	+	*Co-precipitation and flocculation*
									Pelagic viruses	*PV*	–	*Co-precipitation and flocculation*
3) *Return water discharge*	*Dissolved metals* **Water quality*	*P3a*	*Concentrations of iron, manganese, cobalt, copper, nickel, zinc, cadmium, arsenic, lead and vanadium (nmol/l or nmol/kg) in the water column*	*Dispersive*	*Continuous*	*Persistent*	*No*	*Yes*	*Migrating micronekton*	*MMn*	–	*Nodule metals toxicity*
									Deep nekton	*DN*	–	*Nodule metals toxicity*
									Protistan grazers	*PG*	–	*Nodule metals toxicity*
									Pelagic viruses	*PV*	–	*Nodule metals toxicity*
									Zooplankton	*Zp*	–	*Nodule metals toxicity*
									Pelagic chemoautotroph s	*PCa*	+	*Nodule metals toxicity*
									Free-living oligotrophs	*FO*	+	*Nodule metals toxicity*
	Dissolved oxygen	*P3b*	*Oxygen concentration of water (mg/L); this pressure is only*	*Dispersive*	*Continuous*	*Transient*	*No*	*No*	*Deep nekton*	*DN*	–	*Increased oxygen*

Activity/ source	Pressure	Code	Definition and measure	Spatial extent	Frequency during operations	Persistence after operations)	Potential to accumulate *in situ* over time	Potential to bio-accumulate	To	Code	Sign	Direct effect
			relevant if discharge is within the oxygen minimum zone, where background oxygen concentrations are low									
	Organic matter	*P3c*	*Organic matter content of suspended solids (mg/L) from discharged seabed material taken up by the collector vehicle and riser system, including any entrained benthic detritus, microbes and carrion*	*Dispersive*	*Continuous*	*Transient*	*No*	*No*	*Carrion*	*Car*	+	*Fresh particulate organic matter*
									Marine snow	*MS*	+	*Fresh particulate organic matter*
									Particulate organic matter	*POM*	+	*Fresh particulate organic matter*
4) Riser system	Riser noise *Noise	P4a	Decibels (dB) and frequency (Hz) of the noise field emanating from the riser system; the extent of the noise field may be enhanced if the air injection system or pumps are located in the SOFAR (Sound Fixing and Ranging) channel	Dispersive	Continuous	Transient	No	No	Surface nekton	SN	–	Noise from riser pipe and air injection
									Top predators	TP	–	Noise from riser pipe and air injection
									Migrating micronekton	MMn	–	Noise from riser pipe and air injection
									Deep nekton	DN	–	Noise from riser pipe and air injection
5) Collector vehicle sediment plume	*Water turbidity* **Water quality*	*P5a*	*Light scattering in seawater (NTU) by resuspended sediment particles near the seafloor*	*Dispersive*	*Continuous*	*Transient*	*No*	*No*	*Demersal micronekton*	*DMn*	–	*Feeding impairment and reduced visual communication*
									Demersal zooplankton	*DZp*	–	*Feeding impairment, uncertain*
									Sessile suspension feeders	*SSF*	–	*Feeding impairment*

Activity/ source	Pressure	Code	Definition and measure	Spatial extent	Frequency during operations	Persistence after operations)	Potential to accumulate *in situ* over time	Potential to bio-accumulate	To	Code	Sign	Direct effect
									Xenophyophores	*Xp*	–	*Feeding impairment*
									Demersal carnivores	*DC*	–	*Reduced visual communication*
	Suspended sediment particles *Water quality	P5b	Total suspended solids in seawater (mg/L) from resuspended sediment particles near the seafloor	Dispersive	Continuous	Transient	No	No	Demersal micronekton	DMn	–	Respiration irritation
									Demersal zooplankton	DZp	–	Respiration irritation and reduced buoyancy of jellies
									Sessile suspension feeders	SSF	–	Respiration irritation
									Xenophyophores	Xp	–	Respiration irritation
6) Sediment plume deposition	Sedimentation *Seafloor structure	P6a	Depth of sediment deposition on hard or soft substrate (mm)	Dispersive	Continuous	Persistent	Yes	No	Benthic microbial heterotrophs	BMH	–	Burial and smothering
									Hard substrate	HS	–	Burial and smothering
									Infaunal deposit feeders	*IDF*	–	*Burial and smothering*
									Infaunal predators	*IP*	–	*Burial and smothering*
									Sessile suspension feeders	*SSF*	–	*Burial and smothering*
									Xenophyophores	*Xp*	–	*Burial and smothering*
	Nutrient and carbon redistribution *Nutrient and carbon redistribution	P6b	Concentrations of inorganic nutrients in sediment pore waters (nmol/L), including nitrate, nitrite, phosphate, silicate, as well as dissolved inorganic carbon	Dispersive	Continuous	Persistent	Yes	No	Benthic microbial heterotrophs	BMH	–	Nutrient and carbon redistribution, uncertain sign
									Mobile epifaunal deposit feeders	EDF	–	Nutrient and carbon redistribution
	Sediment microplastics	*P6c*	*TBC*	*Dispersive*	*Continuous*	*Persistent*	*Yes*	*Yes*	*Mobile epifaunal deposit feeders*	*EDF*	–	*Microplastic redistribution*

Activity/ source	Pressure	Code	Definition and measure	Spatial extent	Frequency during operations	Persistence after operations)	Potential to accumulate *in situ* over time	Potential to bio-accumulate	To	Code	Sign	Direct effect
									Sessile suspension feeders	*SSF*	–	*Microplastic redistribution*
									Xenophyophores	*Xp*	–	*Microplastic redistribution*
7) Nodule collection	Sediment removal *Seafloor structure	P7a	Depth of sediment removed (mm) in the directly mined area	Localised	Continuous	Persistent	No	No	Benthic microbial heterotrophs	BMH	–	Surface sediment removal
									Benthic detritus	BD	–	Surface sediment removal
									Carrion	Car	+	Surface sediment removal
	Seabed disturbance *Seafloor structure	P7b	Area of seabed mined (m^2) in the directly mined area	Localised	Continuous	Persistent	No	No	Infaunal deposit feeders	IDF	–	Movement of sediment
									Infaunal predators	IP	–	Movement of sediment
	Nodule removal *Nodules	P7c	Removal of nodules from the seafloor (kg/m^2) in the directly mined area	Localised	Continuous	Permanent	No	No	Polymetallic nodules	Nod	–	Nodule removal
8) Collector vehicle	Sediment compaction *Seafloor structure	P8a	Compaction sediment from the collector vehicle (mm) in the directly mined area, influenced by pressure applied by the weight (and buoyancy) of the vehicle (kPa) and the stiffness of the sediment (units to be confirmed)	Localised	Continuous	Persistent	No	No	Bioturbation	Biot	–	Compaction and changes in porewater chemistry
									Benthic microbial heterotrophs	BMH	–	Compaction and changes in porewater chemistry
									Carrion	Car	+	Compaction and changes in porewater chemistry
									Infaunal deposit feeders	IDF	–	Compaction and changes in porewater chemistry
									Infaunal predators	IP	–	Compaction and changes in porewater chemistry, uncertain
									Mobile epifaunal deposit feeders	EDF	–	Compaction and changes in porewater chemistry
	Vehicle noise **Noise*	*P8b*	*Decibels (dB) and frequency (Hz) of the noise field*	*Dispersive*	*Continuous*	*Transient*	*No*	*No*	*Demersal carnivores*	*DC*	–	*Masking of communication and sensory distress*

Activity/ source	Pressure	Code	Definition and measure	Spatial extent	Frequency during operations	Persistence after operations)	Potential to accumulate *in situ* over time	Potential to bio-accumulate	To	Code	Sign	Direct effect
			emanating from the collector vehicle									
	Vehicle tracks *Seafloor structure	P8c	Percent of sediment surface with vehicle track marks versus those without track marks in the directly mined area, creating differential patterns of compacted and non-compacted areas	Localised	Continuous	Persistent	No	No	Infaunal deposit feeders	IDF	–	Migration barriers for infauna, uncertain
									Infaunal predators	IP	–	Migration barriers for infauna
	Sediment surface composition *Sediment and pore water composition	P8d	Stiffness of sediment (units to be confirmed) and average grain size (µm) in surface sediment layers due to compaction and movement of sediment in the directly mined area (to be reviewed)	Localised	Continuous	Persistent	No	No	Sessile suspension feeders	SSF	–	Composition and characteristics of substrate for recruitment
9) Climate change	Ocean stratification	P9a	Increasing ocean stratification (*i.e.*, change in water density with depth) is determined by vertical temperature, salinity and pressure gradients (computed as N^2, the squared Brunt–Väisälä frequency, or buoyancy frequency); stratification influences vertical exchanges of heat, carbon, oxygen and nutrients in surface waters, and is	Regional	Continuous	Permanent	No	No	Water column nutrients	WCN	–	Stratification inhibits vertical mixing of inorganic nutrients in surface waters

Activity/ source	Pressure	Code	Definition and measure	Spatial extent	Frequency during operations	Persistence after operations)	Potential to accumulate *in situ* over time	Potential to bio-accumulate	To	Code	Sign	Direct effect
			enhanced by climate-driven ocean warming									
	Ocean deoxygenation	P9b	Oxygen content of water (mg/L)	Regional	Continuous	Permanent	No	No	Surface nekton	SN	–	Expanded oxygen minimum zone
									Top predators	TP	–	Expanded oxygen minimum zone
									Migrating micronekton	MMn	–	Expanded oxygen minimum zone
									Particulate organic matter	POM	+	Expanded oxygen minimum zone
	Ocean heating	P9c	Water temperature (°C) increases microbial metabolism	Regional	Continuous	Permanent	No	No	Particulate organic matter	POM	–	Increased metabolism of microbes
									Pelagic viruses	PV	+	Increased viral activity
	Ocean acidification	P9d	Acidification of ocean waters (pH)	Regional	Continuous	Permanent	No	No	Demersal zooplankton	DZp	–	Decreased pH
									Infaunal deposit feeders	IDF	–	Decreased pH
									Migrating micronekton	MMn	–	Decreased pH
									Deep nekton	DN	–	Decreased pH
									Sessile suspension feeders	SSF	–	Decreased pH
									Zooplankton	Zp	–	Decreased pH
	Interannual climate variability	P9e	Shift to a productive ENSO regime	Regional	Continuous	Persistent	No	No	Nutrients	WCN	+	Increased mixing or advection of upwelled water
10) Non-mining activities	Fish catch *Commercial fisheries	P10a	Fish caught by fishing vessels (kg/km^2)	Regional	Continuous	Permanent	No	No	Top predators	TP	–	Fish catch
	Shipping noise	P10b	Decibels (dB) and frequency (Hz) of the noise field	Dispersive	Continuous	Permanent	No	No	Top predators	TP	–	Masking of communication and sensory distress

Activity/ source	Pressure	Code	Definition and measure	Spatial extent	Frequency during operations	Persistence after operations)	Potential to accumulate *in situ* over time	Potential to bio-accumulate	To	Code	Sign	Direct effect
	*Noise		emanating from shipping vessels									
	Plastic pollution	P10c	Microplastic particles throughout the water column (mg/L)	Regional	Continuous	Permanent	Yes	Yes	*Surface nekton*	*SN*	–	*Toxicity of plastic particles*
									Top predators	TP	–	Toxicity of plastic particles
									Gelatinous suspension feeders	*GSF*	–	*Toxicity of plastic particles*
									Infaunal deposit feeders	*IDF*	–	*Toxicity of plastic particles*
									Mobile epifaunal deposit feeders	*EDF*	–	*Toxicity of plastic particles*
									Migrating micronekton	*MMn*	–	*Toxicity of plastic particles*
									Marine snow	*MS*	–	*Toxicity of plastic particles*
									Sessile suspension feeders	*SSF*	–	*Toxicity of plastic particles*
									Xenophyophores	*Xp*	–	*Toxicity of plastic particles*
									Zooplankton	*Zp*	–	*Toxicity of plastic particles*

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