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ABSTRACT

Deep-sea mining may be just a few years away and yet society is struggling to assess the positive aspects, such as increasing the supply of metals for battery production to fuel the green revolution, versus the potentially large environmental impacts. Mining of polymetallic (manganese) nodules from the deep ocean is likely to be the first mineral resource targeted and will involve direct impacts to hundreds of km^2 of seabed per mine per year. However, the mining activity will also cause the generation of large sediment plumes that will spread away from the mine site and have both immediate and long-term effects over much wider areas. We discuss what the impacts of plumes generated near the seabed by mining vehicles may be and how they might be measured in such challenging environments. Several different mining vehicles are under development around the world and depending on their design some may create larger plumes than others. We discuss how these vehicles could be compared so that better engineering designs could be selected and to encourage innovation in dealing with plume generation and spread. These considerations will aid the International Seabed Authority (ISA) that has the task of regulating mining activities in much of the deep sea in its commitment to promote the Best Available Technology (BAT) and Best Environmental Practice (BEP).

1. Introduction

Deep-sea mining is a new activity that is gaining momentum with some companies eager to begin in the next few years [41]. It will include the exploitation of three resource types – polymetallic nodules, cobalt-rich ferromanganese crusts and polymetallic sulphides – each of which will impact different ecosystems [26,36,56,86]. Herein, we have concentrated on mining polymetallic nodules and we examine the impact of plumes generated at the seabed and how these impacts might be measured and compared between vehicles. We have not considered mining of other resources or the impact of midwater plumes, generated by dewatering ore on the support vessel as described by Muñoz-Royo [58]. Plumes will spread beyond the mine site forming a halo where particle-laden and potentially toxic plumes generated by the mining vehicle will impact the environment beyond the mine site [1,25,84]. These impacts are expected to vary along a gradient from killing all organisms near the mine site to having no impact distally. We do not know what the distance will be between these two end members, but it is

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likely to range from kilometres to tens of kilometres [1,25], although some older simulations estimate much wider particle dispersion [66]. Suspended particle plumes are likely to spread further horizontally during nodule mining than during crust or sulphide mining [17]. This is because nodules lie on a seabed consisting largely of clay particles that will be suspended by the mining activity, whilst mining the other two resources involves grinding hard rock that is expected to generate smaller plumes with denser particles [86].

Polymetallic nodules are formed in deep ocean basins where sedimentation rate is very low, thus allowing the nodules to grow slowly by precipitation of metals from seawater and sediment porewater [30]. These environments have very clear bottom waters owing to the very limited particle supply [23,76] and the low likelihood of sediment resuspension [64]. The organisms that live in abyssal nodule environments are adapted to very low turbidity and low food supply conditions [76] and have lower metabolic rates owing to the cold temperatures of deep bottom water [7]. The effects of sediment laden plumes, such as those that will be generated by mining nodules, will be much more pronounced than in areas where organisms tolerate bottom waters with higher particle loads [76]. Even very low particle concentrations in plumes may have a significant impact, especially if they continue for long periods of time (chronic effect) [43,89].

Ecosystems associated with polymetallic nodules are thought to recover extremely slowly (decades to centuries) or potentially not at all, shifting into an alternate regime [71] based on benthic impact experiments that have simulated some aspects of mining activities [28,40,72, 81–83]. Uncontrolled spread of plumes generated by the nodule mining process could therefore have a high impact on seabed fauna in areas adjacent to the mined areas [76]. These ecosystems are poorly studied [26,73,87], partly because they are remote from land and because organisms are sparsely distributed over very large areas with many unknown species.

Since deep-sea mining has not yet begun, most information on plume generation is theoretical or based on fine-scale field experiments [61–63,77]. There is also very little information on the impact of plumes on individual organisms and ecosystems. Early papers that modelled the spread of plumes suggested they may have an impact 100 km away from the mine site in nodule areas [66], and this figure was used in the design of buffer zones around Areas of Particular Environmental Interest in the Clarion Clipperton Fracture Zone (CCZ) [88], to prevent impact in the core area. More recently, models have been run based on laboratory experiments that consider the effects of natural flocculation [25] with these models showing a much more limited spread of plumes (< 5 km extent). However, the results in Gillard et al. [24] are based on simulations of a 4-day continuous collector trial (sediment release) and these results might be different for a longer (and more realistic) mining simulation period. In any case flocculation will not remove all sediment particles from the water column. Some of the very fine sediment with low sinking velocity will remain in the water column for a very long time [58]. This process is termed the “rain of fines” by the ISA [33]. Future testing of component parts of mining systems, and test mining of fully integrated mining systems, together with in situ tests, will be important to quantify the amount of material put into suspension and to verify the models of plume spread.

The ISA has a legal duty to set Rules, Regulations and Procedures (RRPs) to prevent, reduce and control pollution and other hazards to the marine environment from seabed mining in Areas Beyond National Jurisdiction (ABNJ), with ‘*particular attention being paid to the need for protection from harmful effects of such activities as drilling, dredging, excavation, disposal of waste…*’ which would encompass RRPs to control the dispersal of sediment plumes caused by seabed mining equipment [ref. Article 145 UNCLOS]. The ISA is currently working to develop such RRPs.

These RRPs will include ‘Environmental Standards’, which would be legally-binding to any contractor carrying out seabed mining activity under the ISA’s jurisdiction (regulations 45 and 94 of the draft Exploitation Regulations) [34]. The ISA has indicated an intention to take an ‘outcome-based approach’ to the development of these Standards [35]. This means that the ISA would set certain environmental parameters and thresholds in its Standards (including those pertaining to permitted plume behaviour, or permitted impacts from plumes), and individual contractors may then take whatever technical or engineering approach they wish to deliver their mining operations within those threshold values. As described by an ISA workshop report: “*An outcome-based approach prescribes for rigorous and contractually binding outcomes, while affording flexibility in the processes by which these outcomes are achieved. This approach incentivizes continuous improvement in technology and encourages innovation and avoids the tick box compliance culture…*” (https://www.isa.org.jm/event/workshop-development-standards-and-guidelines-mining-code). These Standards may themselves be supported by Guidelines, which would not be binding, but which may indicate different recommended ways of achieving the requisite outcomes. This could (in time) include provision of examples of particular technology or mining methods known to have a positive track record, though this would be guidance only and there would be no obligation for contractors to adopt those same methods.

The spread and impact of plumes may be controlled to a certain extent through good equipment design and good mining practice [45]. Different mining vehicles will produce different amounts of waste sediment and may handle that waste in different ways e.g. with more or less entrained water being exhausted at different velocities and heights above the seabed. Management of plume behaviour may also be possible e.g., through electrocoagulation or addition of flocculants that could force most of the ejected sediment to settle close to the mining vehicle. However, flocculants may also have negative (toxic) effects on organisms and research would be needed to weigh any benefits against any negative effects. Thus, the vehicle design and performance may be a significant factor in controlling plume spread and is one area where environmental gains can be made.

Use of good engineering designs and techniques of operation is recognised in the current draft text of the regulations on exploitation of mineral resources that are being developed by the ISA ([34] draft regulation 44). These call for use of the Best Available Scientific Evidence (BASE), Best Available Techniques (BAT) and the Best Environmental Practices (BEP). The ISA defines them as:

> “Best Available Scientific Evidence” means the best scientific information and data accessible and attainable that, in the particular circumstances, is of good quality and is objective, within reasonable technical and economic constraints, and is based on internationally recognised scientific practices, standards, technologies and methodologies.

> “Best Available Techniques” means the latest stage of development, and state-of- the-art processes, of facilities or of methods of operation that indicate the practical suitability of a particular measure for the prevention, reduction and control of pollution and the protection of the marine environment from the harmful effects of exploitation activities, taking into account the guidance set out in the applicable guidelines.

> “Best Environmental Practices” means the application of the most appropriate combination of environmental control measures and strategies, that will change with time in the light of improved knowledge, understanding or technology, taking into account the guidance set out in the applicable guidelines.

It is therefore important to establish which mining vehicles have the best performance in terms of causing the least impact to establish the BAT. In this paper we consider how this might be achieved in a practical way involving the testing of the performance of each vehicle in the operating environment.

These issues were discussed in a virtual workshop held in late 2020 with some of the participants from three European research projects MIDAS (http://www.eu-midas.net/), MiningImpact (https://miningimpact.geomar.de/) and Blue Harvesting (https://blueharvesting-project.eu/). The workshop included 14 experts (all co-authors of this paper) with knowledge of the biogeochemistry, biology and ecotoxicology of manganese nodule environments, plume modelling, geology, in-situ instrumentation for environmental monitoring, developing nodule mining equipment and associated environmental impacts, and legal aspects of deep-sea mining. This discussion can be regarded as an early phase in the development of a standard method for classifying vehicle impacts that if feasible could be developed into a standard meeting the requirements of the International Organization for Standardization (ISO).

2. Background to the nodule mining process

Polymetallic nodule occurrence of economic interest is largely limited to four locations [56]: the CCZ in the north-central Pacific Ocean, the Penrhyn Basin in the south-central Pacific, the Peru Basin in the south-east Pacific, the Peru Basin in the south-east Pacific and the Central Indian Ocean. Seventeen of the nineteen polymetallic nodule exploration contracts that have been granted to date by the ISA in ABNJ are for areas in the CCZ, one is for exploration in the Indian Ocean and one is in the Western Pacific. Fig. 1 shows the concentration of contracts that have been awarded in the CCZ. In total they cover 1.25 million km^2.

In the CCZ the seabed is composed of soft muds with nodules lying strewn across the surface. The nodules are generally potato sized [76] and must be removed from the mud as part of the mining process. Multiple concepts have been developed around the world for extracting nodules. Mechanical collectors will disturb the seabed by digging up the nodules and then 'washing' them before transferring them to the vertical transport system. Hydraulic collectors are under development, with the majority being based on the Coandă effect [39]. The Coandă effect allows water jets to be directed parallel to the seabed where they have maximum impact on lifting nodules together with some sediment. A third alternative is the draghead design, as used in conventional dredging, that directs jets of water at the seabed where the whole top layer is eroded. All mechanisms collect the surface sediment together with the nodules, though a new idea of collecting nodules with minimum sediment has recently been suggested (https://impossiblemining.com/). The nodules and sediment are drawn into the mining vehicle where the nodules need to be separated as much as possible from the sediment. This sediment is ejected as a slurry at the back of the vehicle where it will settle to the seabed and form a soupy layer (Fig. 2). Gillard et al. [24] recorded 28% of the sediment from the German contract area in the CCZ to have a grain size less than 10 μm, 57% to be between 10

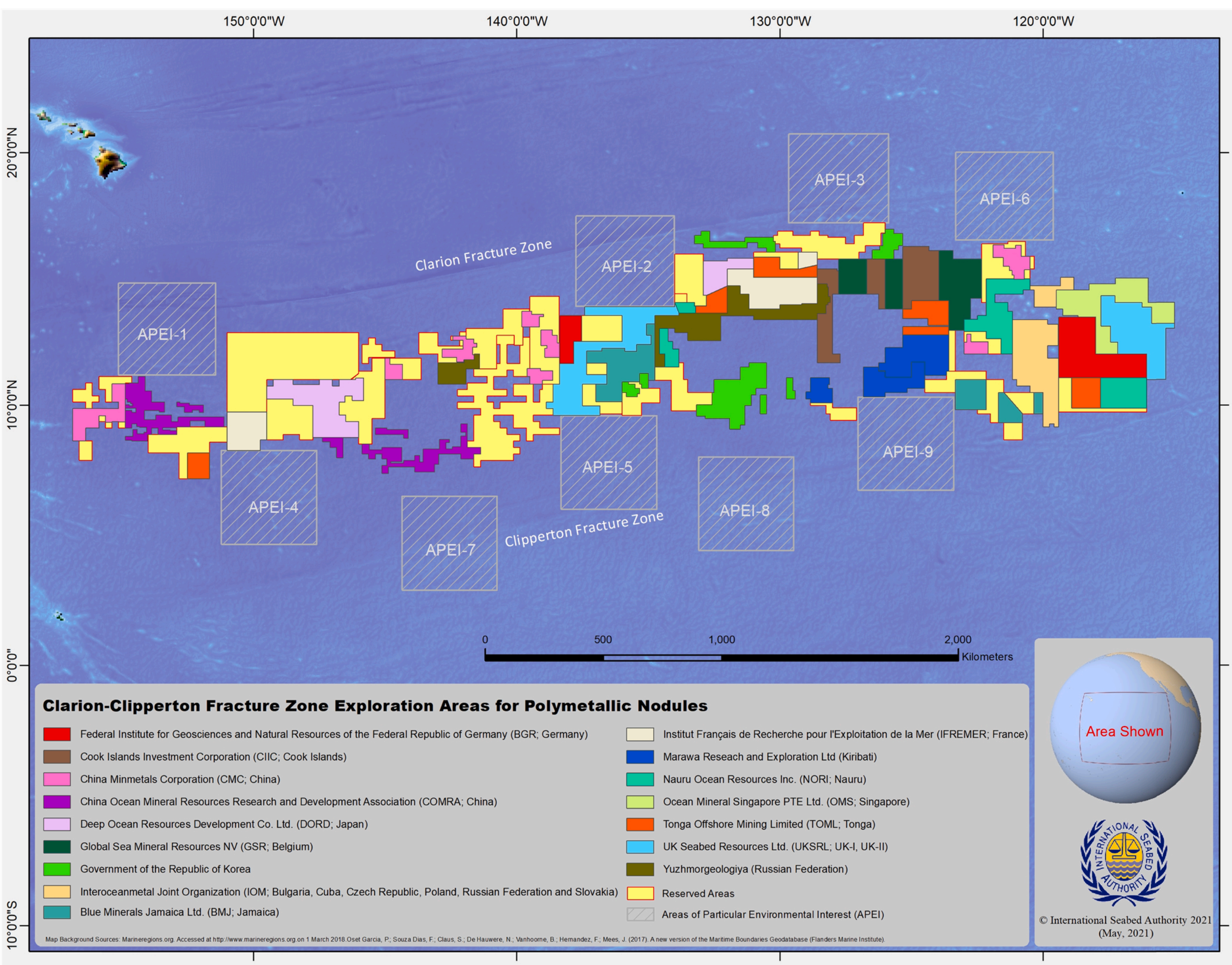

Fig. 1. Areas of exploration contracts awarded by the ISA in the Clarion Clipperton Zone of the Pacific Ocean as of 2021. The total area covered by exploration contracts in the CCZ covers 1.25 million km^2.
Source: https://www.isa.org.jm/map/clarion-clipperton-fracture-zone (Accessed 10 February 2022).

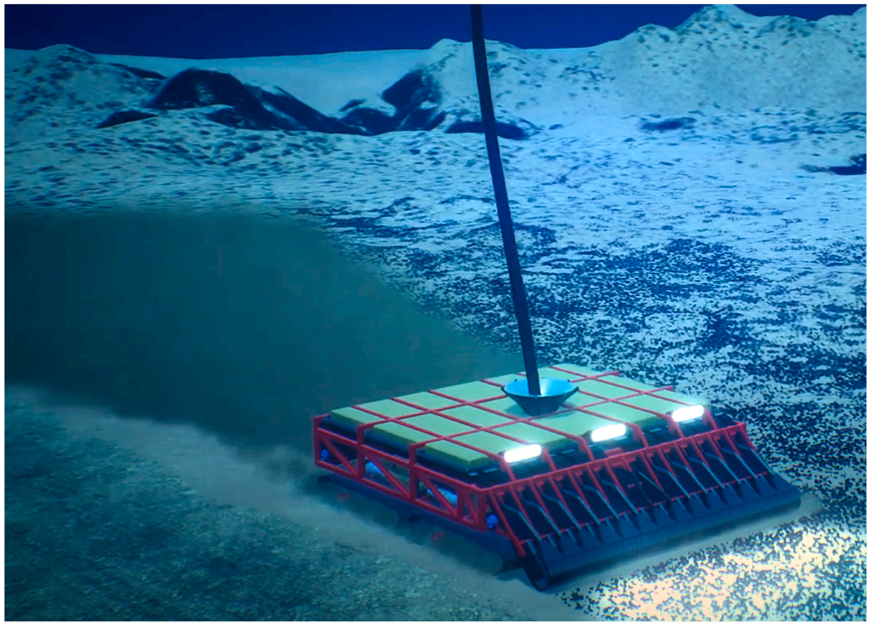

Fig. 2. Artists impression of mining vehicle traversing the seabed collecting nodules and creating a plume.
Source Blue Nodules video https://www.youtube.com/watch?v=pCus0hTsibc&feature=youtu.be (Accessed 10 February 2022).

and 63 μm and 15% to be greater than 63 μm. Most of these particles form rapidly sinking aggregates, while a proportion of the finer grain sizes may remain in suspension and be carried away as a plume by the prevailing current to produce a 'rain of fines' over a much wider area. An additional plume of fine-grained particles will be created by the returned water. The returned water plume is not considered further here as it is not generated by the mining vehicle.

During nodule mining, it is expected that in the order of 30,000 m^2 of seabed will be mined per hour resulting in the extraction of 300–400 tons of nodules – equivalent to mining an area of ~200 km^2 to recover 2–3 million tons of ore per year (Blue Nodules video commentary – available at https://www.youtube.com/watch?v=pCus0hTsibc&feature=youtu.be). If the seabed is mined to a depth of 6 cm, as is envisioned from development of pre-prototype nodule collectors [6], this will result in the collection of around 1800 m^3 of sediment (particles and porewater) per hour.

Each exploitation contract area can be up to 75,000 km^2 in area and mine sites will be selected within it depending on nodule concentration and local topography. It has been estimated that 20–30% of the contract area may be mined over a 30-year contract (contract length mentioned in draft exploitation regulations [34]). Fig. 3 shows a hypothetical contract area with three mine sites. If plumes have a widespread impact as shown in the upper panel much of the contract area could be affected as well as neighbouring areas outside of the contract block. Tight control of plumes, as shown in the lower panel, leaves large unaffected areas (light blue) that could serve as refugia for the nodule-associated fauna and significantly reduce impacts outside of the contract area. It would also provide more options for locating Preservation Reference Zones (PRZs) and lead to less impacts on adjoining contract areas.

The degree to which mining vehicles are designed to reduce the generation and spreading of plumes should therefore be a key criterion in the environmental classification of vehicle impact.

Several of the contractors are known to be building their own nodule mining vehicles and other companies are also building prototype mining vehicles e.g. Royal IHC in the Netherlands [6]; Global Sea Mineral Resources (GSR) (in GSR Environmental Impact Statement available at https://economie.fgov.be/sites/default/files/Files/Entreprises/deep-see-mining/isa-eia-2018-gsrnod-2019.pdf accessed 3rd February 2022); The Metals Company/Nauru Ocean Resources Inc (NORI) (in NORI environmental impact statement available at https://static1.squarespace.com/static/611bf5e1fae42046801656c0/t/6152820c295c1543ff79796c/1632797221691/NORI-D+COLLECTOR+TEST+EIS_FINAL_ABBREVIATED_RE.pdf Pages 3–11–3–14 accessed 3rd February 2022). The known organisations that are developing nodule mining vehicles are listed in Table 1 below, although due to commercial sensitivities, information is very limited for most of the vehicles under development. There is therefore likely to be a number of different nodule extraction techniques and potentially a range of mechanisms for dealing with plumes each with a different size of environmental impact.

3. Measuring plume impact

At present, there is some uncertainty around the impact of plumes generated by nodule mining but providing a consistent approach for comparing the environmental impact of mining vehicle operations is valuable. One way that the impact of different mining vehicles could be compared is through plotting plume impact curves (Fig. 4). Each of these curves envisages complete ecosystem destruction adjacent to the mined track with impacts reducing with distance from this point as the particle load of the plume dissipates and the blanketing thickness becomes thinner. The distances on the x axis are unknown but could be tentatively considered as kilometres based on existing plume models (e.g. [25]). The solid red and upper (dotted) curves represent the response of two different mining vehicles with different plume generation properties. The lower dashed blue curve represents plume impacts where technological mitigation options have been applied e.g. through reducing the water content of the outflow. The solid black curve represents a situation where the plume is forced to deposit close to the mine site due to the use of non-toxic flocculation. The last two examples portray the rain of fines to be very much reduced in the far field, but whether this can be achieved is unknown.

Determining the integrated impact curve of any mining vehicle may be difficult but would allow a direct comparison between technological options important in determining the BAT, which could then be taken up by other vehicle manufacturers. It may be difficult to replicate the test for different vehicles on the seabed since a number of factors would need to be constant such as terrain, biological abundance, ecosystem functions, currents etc. Presumably each vehicle would need to be tested in

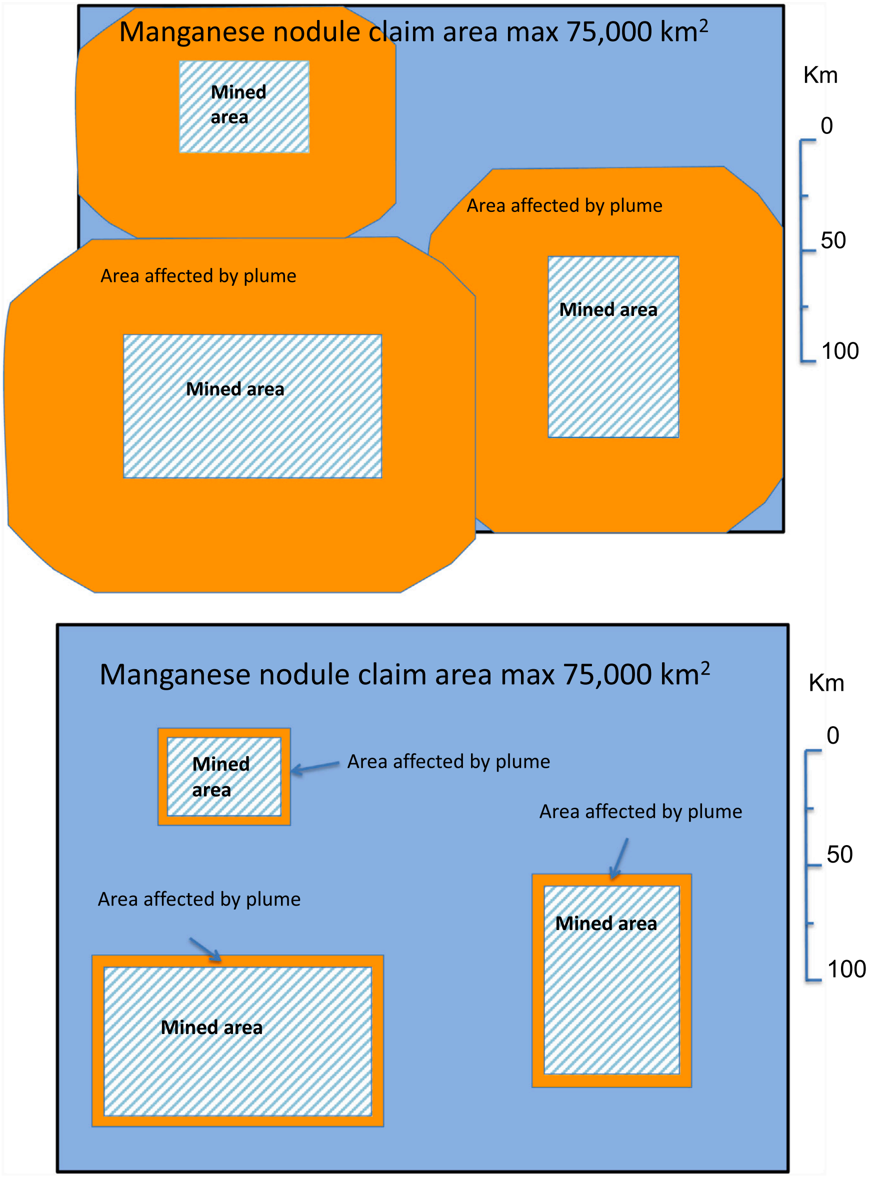

Fig. 3. Plan view of hypothetical contract area **(large box)** with three areas of mined deposits. Blue areas represent pristine seabed unaffected by mining; blue diagonal pattern represents mined areas; orange represents seabed areas affected by the plume. Upper panel shows an area that could be impacted by plumes that spread tens of kilometres from the mined area. Lower panel shows areas that could be impacted if plume spread is controlled to just a few kilometres away from the mining operation.

the contract block where it was to be used. In this case it may be possible to specify some parameters for the test location. In the laboratory the near field dispersion of the plume could be tested by measuring flowrate and concentration of the ejected plume, but it would not be possible to test the full plume dispersion.

Ultimately, it may not be possible to measure the impact of each vehicle in comparable operating environments, but it may be possible to determine the relationship between the physical aspects of the vehicle's sediment exhaust and plume spread/impact e.g. flow rate, sediment concentration, height of plume release, vehicle speed, fluctuating or constant output. These discussions can therefore help towards understanding how plume impacts might be measured and how changes in the shape of the response curves shown in Fig. 4 might be related to the physical aspects. The outcomes of such a comparison could encourage improvements in design of the mining vehicle and/or nodule mining process e.g. electrocoagulation (as mentioned in relation to Deep Reach Technology – see https://arpa-e.energy.gov/technologies/projects/improved-nodule-collector-design-mitigate-sediment-plumes accessed 3rd February 2022), or use of non-toxic natural additives such as organic flocculants produced on large scale from local algae assemblages. These flocculants could also help to restore the organic carbon content of surface sediments. Their benefits would need to be weighed against any negative effects.

4. Discussion

The above assessment shows that it will be challenging to measure the mid-range and far-field effects of plumes on seabed organisms. We attempted to address them in our workshop discussions which concentrated on the following questions:

- What plume parameters are the most important to measure?
- Can the required measurements be made and how?
- Are indicator taxa suitable for measuring plume impact?
- How can biological tolerances to plumes be determined?
- Over what timescales do measurements need to be taken?

The following account highlights some of the issues and suggests some practical ways forward in considering each question.

Table 1
Nodule mining vehicles under development.

Contractor/ Organisation	Mining Vehicle	Notes
GSR	Patania III	Tracked vehicle with hydraulic nodule collection based on Coandă effect (Information available at economie.fgov.be/sites/default/files/Files/Entreprises/deep-see-mining/isa-eia-2018-gsrnod-2019.pdf accessed 3rd February 2022 accessed 3rd February 2022) Patania I and Patania II vehicles have been successfully tested in the operational environment of the CCZ (information available at https://miningimpact.geomar.de/documents/1082101/1433168/Smith_StakeholderID_2021.pdf/392bba75–469e-41ea-af34–3f41ad1fa021 accessed 10 February 2022)
The Metals Company (on behalf of NORI)		Tracked vehicle with hydraulic nodule collection based on Coandă effect. (Information available at https://static1.squarespace.com/static/611bf5e1fae42046801656c0/t/6152820c295c1543ff79796c/1632797221691/NORI-D+COLLECTOR+TEST+EIS_FINAL_ABBREVIATED_RE.pdf accessed 3rd February 2022)
Royal IHC	Apollo III	Tracked vehicle with hydraulic nodule collection based on Coandă effect. (Information available at www.royalihc.com/en/products/mining/dredge-mining-and-deep-sea-mining/deep-sea-mining accessed 3rd February 2022)
KIOST, South Korea	MINERO II	Hybrid hydraulic-mechanical (mechanical collection + hydraulic transport) [31,38]
NIOT, India		Mechanical nodule collection vehicle [3]
SMD	QC2000	Tracked hydraulic collector vehicle (Information available at www.smd.co.uk/our-products/uncategorized/qc2000/ accessed 9 February 2022)
COMRA, China		Tracked double jet hydraulic collector [38]

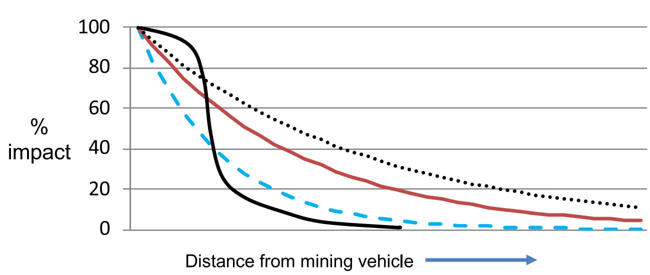

Fig. 4. Graph showing hypothetical decrease of plume impact with increasing distance from mining activity. Note units for distance are unknown. Upper two curves (dashed and solid red) represent differences between different vehicles; lower curves (blue dashed and solid black) represent reduced impact owing to improved design or other intervention.

4.1. What plume properties are the most important to measure?

There are no existing standards for managing deep-sea plume composition, volume or behaviour. Based on the workshop discussions, the following properties were considered important for the setting of any future standard:

1. Seabed particle composition, shape, size distribution: these are important because they affect aggregation behaviour and thus control settling rates. In the CCZ, the dominant sediment type varies from very small sized biogenic silica and clay minerals (≈ 4–10 µm) in the northern and central area to calcareous ooze of increasing particle size (< 100 µm) in the southern area [19,85]. Particle shape may help determine biological effects [79].
2. Vehicle exhaust material: the mixture flowrate and turbulence alongside the concentration and size of particles, including crushed ore material, that is ejected from the mining vehicle may be one of the most critical parameters, since the concentration of particles in the plume determines the natural flocculation potential [25]. The particle content will be controlled by the depth and area of excavation and its duration. Its concentration will depend on the amount of water ejected with the sediment.
3. It is also important to know if the production rate of the plume will remain constant, or will vary e.g. if different substrates or nodule characteristics require a different depth of mining thus entraining more or less sediment. The full range of volumes of waste production from the vehicle will need to be considered. Whilst sensors on fixed or mobile platforms provide essential data on the variation in suspended particle load at discrete locations, numerical models validated and calibrated with field data are indispensable for producing a comprehensive overview of the dispersion of suspended solids in space and time. It will be important to use units of concentration (e.g., grams per litre) throughout, which are easy to produce from the exhaust data but will require calibration of the optical and acoustic data since these are measured in attenuation or backscatter intensity (dB).
4. Thickness of plume deposition on the seafloor (blanketing): the total sediment deposited on the seabed will determine the impact on the biological community and biogeochemical process rates and fluxes. The natural sediment deposition rates in areas such as the CCZ are below 1 cm kyr^{-1} [55] and hence it is predicted that even very low levels of particle input from plumes may be detrimental [76]. This is likely to be even more important if the plume deposition continues for prolonged periods such as months or years leading to chronic effects. Measuring the tail of plume deposition at millimetre scale and below will be difficult or impossible on the seabed, but this information can be derived from numerical models of plume dispersion. Such numerical models, validated and calibrated with field data, are indispensable for producing a comprehensive overview of the dispersion of suspended solids in space and time. A methodological approach is recommended combining field data collection with different classes of state-of-the-art ocean circulation and sediment modelling tools. Potential modelling tools should be capable of describing site-specific processes at the mine site (estimating how efficiently flocculation removes sediments from the water column in the immediate vicinity of the mining vehicle) and predicting dispersal of suspended plumes on scales of tens of kilometres from months to years. Dispersal will be affected by topography as well as currents. This approach requires the high-quality field data described above to facilitate strong predictive power of the numerical models at the mining site and beyond.
5. Metallic content, including particulate, dissolved and colloidal phases: these will have different dispersion and uptake dynamics [22]. Different metal redox and complexation states will partly determine their bioavailability and toxicity to organisms. The size and sharpness of edges of any particulates, or the reactive surface area created during crushing/processing will also contribute to the toxicity effect [44,74,75].

4.2. How can each of these important plume parameters be measured?

There are practical limitations to the level that different plume properties can be measured using existing technology. Taking physical measurements of particle properties should be relatively easy, as should measuring the volume of sediment and water discharged through the vehicle's exhaust. Measuring the layer of sediments deposited from plume settlement is likely to be more challenging especially distally where the layer may be very thin (a few mm's). In these far-field areas, novel techniques like sediment profiling cameras may be needed to accurately measure deposited sediment layers less than a few mm thick. The MiningImpact project (http://jpi-oceans.eu/miningimpact-2) is currently investigating the use of fluorescent-dyed particles to more accurately measure sediment deposition from plume settlement. The presence of acute manganese-resistant bacteria from nodules could on the other hand be used as an indicator for sediment plume dispersions within the water column [25].

Deep-sea research is increasingly oriented towards examining how biodiversity changes, involving organisms across a wide range of ecological sizes, affect ecosystem function and service provision [13]. Biological indicators for environmental impacts have long been a key metric used in marine environmental monitoring. Potential indicators include presence or health of indicator taxa (for example sponges may be a sensitive indicator of sediment impact), population/community metrics (for example assessing biodiversity changes) or functional indicators (for example assessing changes in key ecological rate processes). At present, there is insufficient information to link biological changes to specific levels of plume disturbance.

In addition to their value as indicators, biological metrics reflect some of the key societal and management concerns about mining impacts. Assessment should include focus on the most critical issues. For example, when measuring contaminant levels in plumes, effort should be directed to those compounds that are most toxic to biological communities, weighted by the percent composition within a given nodule field. Consideration should be given to the degree of toxicity associated with different phases, such as the particulate, dissolved, and colloidal forms of metals. For example, natural metal-rich nanoparticles may be present (e.g. [32]) and their distinct physico-chemical properties will create different interactions with the biota that potentially trigger worse effects than dissolved metals [59,69].

4.3. Are indicator taxa suitable for measuring plume impact?

At present, little is known of the responses of deep-water organisms, populations or communities to particulate load, plume toxicity or deposited sediment thickness from mining activity [37,54]. Results from shallow water can not necessarily be transferred to deep-sea systems [29] and ex-situ experiments are typically less informative. Compiling the data on impacts requires in situ experimentation or observation of deep-sea sediment impact gradients across a wide range of species and faunal classes, which is a large task. Ideally, biological tolerances to plumes would be determined across the full size-spectrum of benthic and pelagic organisms. Unfortunately, there are multiple practical constraints to such an approach, and it may be more feasible to seek indicator taxa that reflect the wider impacts on other species. Indicator taxa may need to be specific for distinct areas, as recent studies suggest high hidden diversity and limited distribution of species (e.g. [5,10,57]). Thus, in addition to the usage of a single indicator taxa to detect impact, it may be more efficient to determine suitable biological indicators, which address the nature of the impact considered, spanning from impact on individuals, populations, communities, or ecosystem function.

Large (megafaunal: >1 cm; [78]) sessile organisms (e.g. sea pens, anemones, sponges, corals) may make particularly suitable indicator taxa, given that they are unable to escape plumes, often have feeding modes that are susceptible to impacts from particulates and should be identifiable on camera and video images [15]. They may, however, have a lower contribution to ecosystem function than smaller (macrofaunal, meiofaunal, protozoal, or microbial) organisms [80], including benthic (micro-)bioturbating species (e.g. polychaetes, nematodes) and thus, may not be representative for the overall status of ecosystem health. Megafaunal organisms can be very sparsely distributed in nodule provinces such as the CCZ, requiring large areas of seafloor (km^2) to be surveyed to determine community-level impacts [2]. This may be achieved (e.g. [72,73]) with the emerging technology of resident seafloor robots and Autonomous Underwater Vehicles (AUVs). Baseline studies are essential to assess the pristine status of the ecosystem and distribution of the indicator taxa before mining begins and the ecosystem becomes altered or impacted [14]. These baseline studies should anticipate where measurements and surveys will be needed to assess plume impacts once mining begins, and this planning should be part of the approval process for the contractor's Environmental Impact Assessment (EIA).

Assessing impacts to smaller organisms cannot be achieved using images and videos and, in this case, physical sampling of the seabed would be required. Focussing on smaller organisms would mean that smaller survey areas could be used to obtain sufficient sample replicates and this may be more informative for detecting impacts over smaller spatial scales. It may be possible to use some macrofaunal or meiofaunal species as indicator taxa and/or to monitor community composition and/or function to detect changes at more rapid rates or as a result of different sensitivities.

One possibility would be to combine visual imaging surveys of megafaunal taxa with replicated point sampling for macrofaunal and meiofaunal taxa along the same transects away from the mined area. In this way a rapid assessment could be made from the imagery data that could then be augmented by the point samples. In all cases multiple transects should be carried out away from the mined area including one in the direction of the prevailing current. This overall concept was followed by the MiningImpact project in the course of the independent scientific study of the nodule collector trial conducted by GSR [27].

4.4. How can biological tolerances to plumes be determined?

Different organisms may show different tolerance levels to plumes and some may show little impact initially with impacts only becoming apparent after a prolonged period. Some organisms may be more sensitive to particle load than low-level toxins, or vice versa. To date we have very little data and so a range of measurements will be necessary. The potential methods for measuring tolerances of indicator taxa/biological indicators to plumes include:

Population or community measures:

1. Seafloor imagery to determine changes in abundance, volume/size, distribution or behaviour of megafaunal organisms, including movement away from impacted areas, or changes to bioturbation observed through lebensspuren (sedimentary structures caused by organisms e.g. tracks, burrows). This should include both assessment in space (transects) and time (time-lapse imagery, repeat surveys).
2. Sediment sampling-based approaches to determine changes in abundance, biomass and distribution of a range of infaunal size classes.

Individual organism measures

1. Use of tissue chemical accumulation and biomarkers in large or small organisms to detect sub-lethal stress of organisms.
2. Conducting toxicity bioassays (median lethal concentration – LC_{50} or median effect concentration – EC_{50} tests) on large or small organisms to determine the relative impact of plumes generated by different collector vehicles.
3. In situ individual-level responses to disturbance e.g. behavioural, functional/ physiological (e.g. metabolic) or pathological. These can be measured using direct observation (with video) or by making process measurements (e.g. respiration rate).

Functional measures

1. Measurements of sediment and benthic chambers using microsensors to determine in situ responses e.g. sediment community oxygen consumption.

2. Measurements of in situ changes in organic matter remineralization, food transport or bioturbation in the sediment as proxies to monitor changes to ecosystem function in the sediments.

To determine the thresholds to the physical aspects of collector-generated plumes, in situ experiments on indicator taxa or on communities, or ex situ experiments on proxy taxa would be needed. These experiments could help to determine the degree of mortality or sublethal stress in response to different thicknesses of sediment blanketing for example, or exposure to particles of different sizes or concentrations. Additional techniques, such as Peptide Mass Fingerprinting (PMF), metabarcoding, or eDNA methods may support more rapid biological sampling to monitor plume impacts on communities over greater horizontal spatial scales and vertically in subsurface sediments, however, more work will be needed to assess its applicability [65,67].

Assessing the response of attached megafaunal taxa may be achievable using seafloor imagery. Although large areas of seafloor may need to be surveyed it is feasible to obtain sufficient spatial coverage and sample replication using image platforms such as AUVs [73] and crawlers [9,16], which can monitor changes of benthic community structure along a gradient away from the disturbance sites. The feasibility of this approach would be limited by the time needed to analyse large numbers for seafloor images, although improvements in automated image analysis via Artificial Intelligence can help to address this in the future [46–48]. The investigative methodology is also critical since small changes in the operational altitude of AUVs or ROVs, illumination and lens type can alter estimations of community structure [68] especially if comparisons are to be made between the impacts of different mining vehicles under similar operational conditions. A standard would need to be established as happens in equipment use in other offshore industries, such as seabed sampling in the offshore hydrocarbon industry (e.g., [60]).

Biochemical tissue biomarkers can be used to detect sub-lethal changes in organisms exposed to the plume, which may act as an early warning system to detect stress, before such changes negatively and permanently affect individual, populations, or ecosystems (e.g., [52]). Ideally a range of organisms should be tested to capture differences in sensitivity. Smaller organisms should be considered as their size would make it easier to achieve sufficient replication. These measurements require seabed sampling from which biological samples can be selected and measured. A careful plan to optimise the location of sample stations would be required, including for example a Before-After-Control-Impact (BACI) sampling approach [70].

There have been very few studies of ecotoxicology in deep-sea organisms and those that have been published show complex patterns that require further research [11,12,29,4,49–51]. To make progress in this area it would be necessary to know the mineral resource composition, exposure route and duration, and to examine multiple taxa as the response may be different for different taxa or functional groups. We therefore suggest that samples should be compared to an agreed standard to determine relative degrees of toxicity, instead of an absolute toxicity profile based on the specific metal composition of each plume. However, for such a standard to be biologically meaningful, there would need to be some supporting information on the tolerance of selected indicator taxa to these contaminants.

Dose-response toxicity tests in situ are very difficult to conduct [42] and conducting such tests on deep-sea organisms under atmospheric pressure at the surface would not be informative, given the physiological alterations they suffer with decompression and the fact that an important environmental parameter would be eliminated from the assessment [29]. Nevertheless, it can be useful to further develop minimal inhibitory concentrations tests with fast growing bacteria collected from the deep sea and cultivated onboard [25] to estimate toxicity of the plume. The most sensitive strains of bacteria should be selected in this case. Still, even in experiments with larger organisms, run under high-pressure aquaria, current methodologies are limited and continuous renovation of seawater with contaminant maintaining high pressure is not possible (e.g., [4]). Instead, toxicity bioassays (LC_{50} or EC_{50} toxicity tests) would need to be conducted on suitable shallow-water proxy species at the surface, for example microorganisms, macro and megafauna. Acute or chronic effects, species from different trophic levels and different life stages should be investigated (e.g., [21]). Early life stages should be particularly considered in these tests as they are usually far more sensitive than the adults (e.g. [53]). The results of these tests would not be directly applicable to deep-sea organisms but could be used to determine the relative toxicity of plumes generated by different collector vehicles.

4.5. Over what timescales do measurements need to be taken?

When full-scale mining begins the impact of particle load from plumes will be highest near the source where it is likely to overwhelm organisms and bury many of them. Sessile epifauna may be killed by this process due to burial near the source and loss of their ability to feed as a result of the particles blocking the feeding mechanisms at a greater distance from the source. Further away, death may not be immediate but the persistent impact from plumes may lead to chronic effects that are likely to weaken and/or kill the sessile epifauna. Mobile epifauna may be overwhelmed near the plume source but may be able to escape areas with lower particle input. Infaunal organisms may be impacted near the plume source if a significant new sediment layer is added, which may change the properties of the seabed e.g. by creating an non-cohesive sediment layer (fluid mud) with high water content; by destroying the surface biologically active layer; and by altering the rate of oxygen and nutrient exchange between the sediment and overlying water column. The tolerance of infauna to plume impacts and deposition of new plume settlement layers is unknown. Hence monitoring may be required over periods of years to pick up long term effects.

The impact of toxicity from plumes may follow a similar pattern but the distances over which the toxicity will have an impact may differ considerably from those related to particle load. Different organisms may also have different responses, some being more susceptible than others [54]. Shallower water studies show that for instance sponges at contaminated sites have inhibited growth and fecundity [8].

For all of the above impacts there will be a temporal factor. This may be short for the sessile epifauna that are killed near the plume source but could increase away from the source where long-term exposure becomes the issue, and which may affect different groups of organisms in different ways. It may also be different for particle load vs toxic impacts. We do not know how long it will take for chronic effects of either particle load and/or toxicity to become visible in the far field of plume impacts, but it could take years to decades, depending on the taxa considered.

In the context of providing environmental accreditation for a nodule-collection vehicle, there may need to be a compromise between measurements being taken over biologically meaningful timescales and assessing vehicle environmental performance in a timely manner to support the development of equipment that can set the highest possible environmental standard for BEP and BAT.

We suggest that measurements may need to be taken over days and weeks to assess acute responses, and months to years to assess sub-lethal responses on biological communities. These measurements will be additional to those used in developing the EIA which may be useful for setting baselines. One option could be to measure biological responses over a full reproductive cycle, for organisms where this is known, since the response may vary with this cycle [18,20]. Assessing chronic responses may not be possible with respect to determining vehicle performance, given the potentially long timescales involved. However, they will be necessary to determine the overall impact of deep-sea mining.

5. Conclusion

It is anticipated that plumes will cause one of the major impacts from deep-sea mining and thus the ISA will need to establish thresholds for the permitted level of impact from plumes. Determining the effect of plumes on organisms will not be easy as discussed above but needs to be urgently addressed. Only when these relationships are understood will it be possible to develop monitoring strategies and regulatory standards. We suggest that this work is carried out before standards and guidelines to deal with plume impacts are developed by the ISA.

The highest priority is to determine the response of organisms to plume impacts including particle load and toxicity. As described above some effects may be immediate, particularly at high levels of plume impact, or in very susceptible taxa. These will require a series of in situ plume experiments. It will be much more difficult to determine long-term effects, but these may be critical as mining in the CCZ will continue for an initial period of thirty years and potentially much longer than this. These more hidden effects may also extend over much wider areas of seafloor, since the plume tails may spread long distances.

In parallel we recommend the determination of the environmental pressures from test mining using size-scaled vehicles that could be used to build a picture of which vehicle design parameters correlate with plume spread and impact. For example, volume of sediment collected and ejected per unit area mined; volume of water ejected with that sediment; height of exhaust above seabed; shape of exhaust and direction of outflow +/- the use of flocculants. Some or all of these parameters will have a relationship to natural flocculation that may reduce plume spread, or to the formation of fluid mud which can result in gravity flows. Some vehicles may incorporate methods for artificial or natural flocculation. Such analysis should not be limited to the plume itself, but should also consider the nodule collection process. Collector design can be optimised for quantity and/or ratio of sediment and water entrainment, enabling more favourable plume release conditions for minimised dispersion.

Using this information, it should be possible to determine which engineering properties of vehicle design control the generation and spread of plumes and build a model to relate these to the impacts on the organisms described above at least for the shorter timescale effects. The model can then be used to predict the efficiency of the vehicle in terms of plume generation and environmental impact.

Developing this vehicle classification is particularly important as this new industry gets started, since there may be several different competing designs in the early years of mining, some of which may cause more environmental impact than others. Identifying those with least impact will be important to set a high standard for BEP, BAT and Good Industry Practice (GIP).

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